CHAPTER 4. A NEW VARIABLE WATER FLOW CONTROL STRATEGY

4.1 Introduction

It was shown in the previous chapter that it would be feasible to install VSDs on pump and fan electric motors of South African mine cooling systems. Due to research budget limitations, it was decided to focus only on pumps in this study. This is because pumps represent a larger percentage energy usage on a typical cooling system when compared to fans. It would, however, be worthwhile to extend the DSM strategy (developed in this study for pumps and water flow) to include fans and air flow modulation in future studies.

The estimated savings and potential for VSDs discussed in Chapter 3 were based on the assumption that the relevant flows can be modulated in proportion to the cooling load and water demand without considering how this will be achieved. It follows that a suitable control philosophy, or set of philosophies, must be developed that enables the VSDs to effectively vary pump rotational speeds to utilise the partial loads effectively. Intelligent control of pump VSDs on a specific system is necessary to realise the energy saving potential that lies in variable speed pumping (Mecrow and Jack 2008). In fact, the successful application of variable water flow depends on how the water flow and chiller capacity can be adjusted and controlled to match changing load conditions (Bahnfleth and Peyer 2004).

Simplicity is often the key to the most elegant and robust design solutions. Furthermore, mine control systems are often preferred to be simple and robust because the harsh environment requires regular maintenance of input and control parameters and instruments. It is best to have as little inputs and controllable factors as possible. A very simple control methodology was therefore proposed. First, all cooling system water pumps should be retrofitted with VSDs. Second, the various pump sets should be controlled so that they merely match their respective water demands. This would have the effects of eliminating the various inefficient control methods, matching supply with demand throughout the integrated system and utilising partial load conditions to achieve this.

The pump sets found on most mine cooling systems are those for pre-cooling tower supply water, evaporator or chilled water, condenser or cooling water, and BAC supply and return water. Simple control philosophies were therefore developed for each of the four generic pump sets, relevant to their respective demands. The four control philosophies collectively form the new variable water flow strategy. Figure 19 shows an overview of a generic mine cooling system with the pump VSDs and control instrumentation of the strategy added.

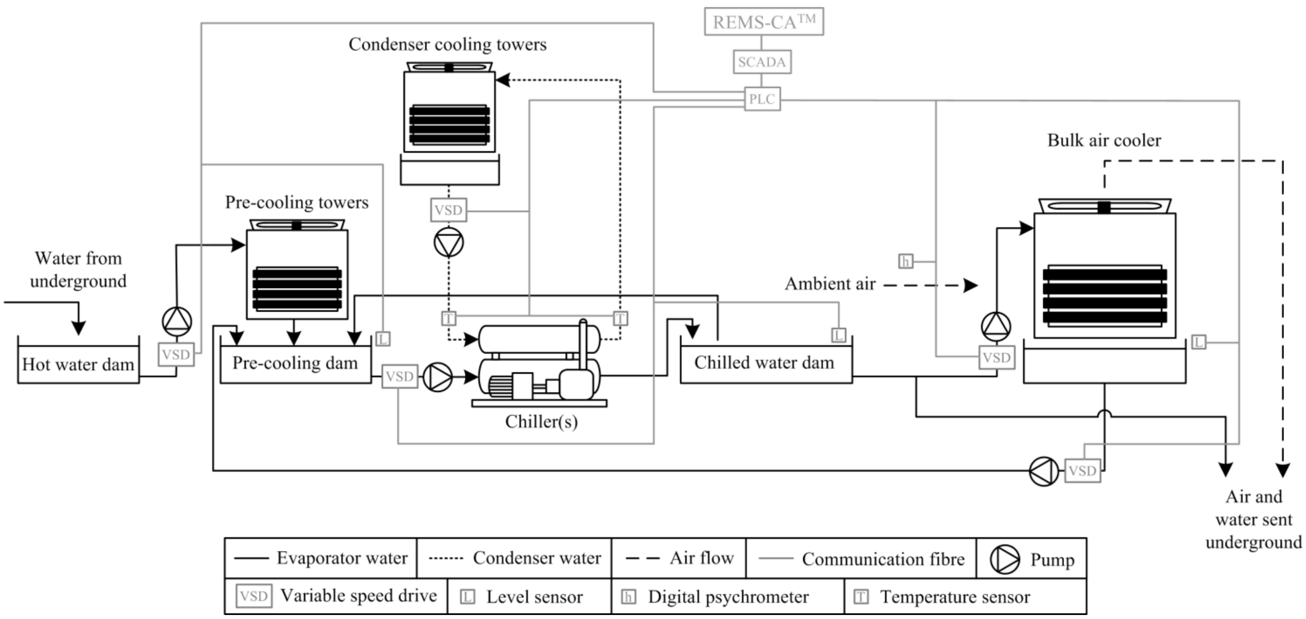

Figure 19 Schematic layout of a simple mine cooling system with variable water flow strategy equipment

Figure 19 shows VSDs installed on the evaporator, condenser, BAC and pre-cooling pumps. Measurement equipment such as dam level sensors, temperature probes and a compact digital psychrometer are also shown. All installed equipment are connected to an integrated network that is controlled from a central energy management system, namely REMS-CA™. This system is discussed in more detail in Chapter 5. Equipment arrangement details depend on the specific site. For example, automatic control valves instead of VSDs might be required to control the water flow to the BAC on sites where the BAC supply water is gravity fed. However, the underlying energy saving strategies remain the same for all sites. Table 11 gives a summary of the generic control philosophies of pump sets.

Table 11 Summary of new variable water flow control philosophies

Pump set	**Variable water flow control philosophy**
Evaporator pumps	Modulate flow to maintain set chilled water dam level
Condenser pumps	Modulate flow to maintain design condenser water temperature rise
BAC pumps	Modulate supply flow in proportion to ambient enthalpy Modulate return flow to maintain set BAC drainage dam level
Pre-cooling pumps	Modulate supply flow to maintain set pre-cooling dam level

Table 11 shows that the proposed variable-flow strategies are simple, but reasonable. They merely address the clear demand of each subsystem while meeting the overall system service delivery requirements of chilled water demand and temperature and BAC air temperature. Each control philosophy shown in Table 11 is discussed in further detail in the following sections. The overview of the strategies form part of the submitted article presented in Annexure B.1.

4.2 Evaporator flow control

The mine cooling system constraint directly placed on the evaporator water line was shown to be the requirement of a specific water temperature that will be available in the chilled water dam on demand (McPherson 1993). The observed mine practices of using valves to throttle the evaporator flow and of recycling overflow water from the chilled water dam back to the pre-cooling dam present the most important energy saving opportunities.

It is proposed to open all existing flow control valves and to install a VSD on the evaporator water pump(s). The pump motor speed is then continuously controlled by means of proportional-integral-derivative (PID) control logic so that a specified chilled dam level is maintained. The strategy control block diagram is shown schematically in Figure 20.

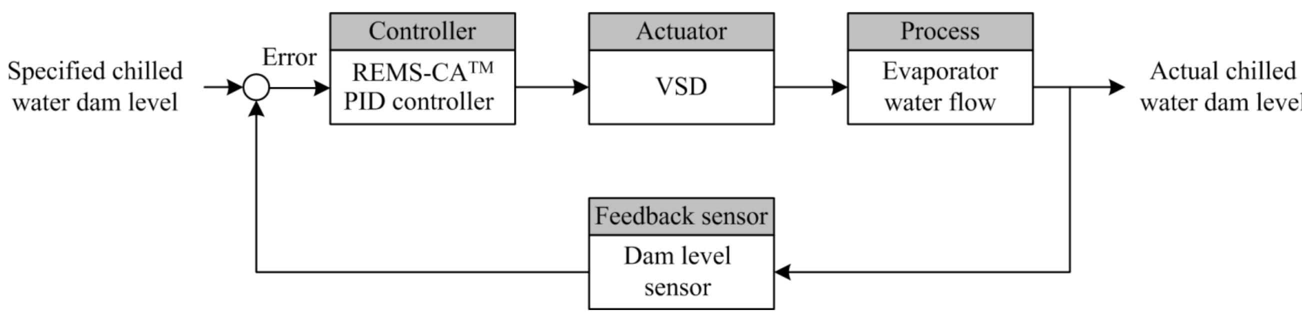

Figure 20 Block diagram of evaporator water flow control

Water pumps are usually overrated as a safety factor in water pumping applications (White 2008). Flow control by means of throttling valves is therefore not energy efficient. The manually operated variable opening valves that are usually used to obtain the required flow must be in the full open position to reduce significant pressure losses when using a VSD. The pump speed will be permanently reduced by the VSD to obtain the original design flow. This alone presents a base energy saving as a result of the cubic power-flow relation (De Almeida et al. 1990). The extent of this saving depends on how much the water pump is overrated and how large the corresponding pressure drop was over the control valve. The practice of flow control by using a VSD to permanently reduce the pump speed is therefore understandably recommended by many equipment manufacturers (KSB 2012).

Part-load conditions are typically defined by inlet water temperatures and ambient conditions below design values in HVAC systems. VSDs installed on evaporator water lines usually modulate the flow in accordance to these loads (Qureshi and Tassou 1996). In mine cooling systems, the chiller inlet water temperature varies somewhat in proportion to the ambient conditions that influence the pre-cooling tower water outlet temperature. The chilled water demand flow was also shown to be intermittent and only occasionally reaches the chiller design flow. The common practice of continuously recirculating chilled water dam overflow to the pre-cooling dam with a fixed chiller design flow thus imposes a higher cooling load on the chiller than is actually required by the mine and integrated cooling system.

The supply cooling load can be matched to the demand cooling load by controlling the chilled water flow such that the dam level remains at a specified value below 100%. This simple method will enable the water flow rate to be reduced below design conditions during times of cooling demands that are below design conditions.

Chiller compressor capacity control methods were shown to maintain the set chilled water outlet temperature. Reducing the water flow should thus not have a significant effect on the outlet temperature, given that the inlet temperature is sufficiently low.

If the water flow rate is fixed at design flow but the inlet temperature is higher than the design value, common mine practice is to recirculate chilled water to reduce the inlet temperature to its design value. Water flow reduction will facilitate a higher inlet temperature for the same full-load condition. Equation 2 can be considered in support of this. It follows that water flow modulation in conjunction with the elimination of water recirculation will not adversely affect the supplied chilled water temperature when inlet temperatures are above design conditions.

During the described conditions where the average inlet water temperature is higher than before strategy implementation, the average refrigerant evaporating temperature will also increase. This will lead to an increase in the compressor suction pressure (McQuay International 2005). The pressure rise across the compressor is now reduced for a set discharge pressure.

In these cases, the compressor capacity control will reduce the refrigerant flow rate and required pressure rise, leading to savings in compressor electrical energy input. Full-load design conditions with water flow below design flow in combination with inlet temperature above design temperature will therefore lead to improved chiller COPs.

The evaporator performance limitations need to be considered when applying the proposed strategy. It is recommended by ASHRAE (2001) that industrial evaporator water velocities never drop below 60% of the design value for the specific chiller. For most shell-and-tube heat exchangers this translates to a velocity at which transition into laminar flow occurs. This reduces heat transfer rates significantly and also increases water-side fouling because of the absence of turbulent flow patterns (Çengel 2006). Subsequent reductions in chiller cooling rates and COP values will follow (Navarro-Esbrí et al. 2010). Most chiller plants are designed to shut down if the lower flow limit is reached. Therefore, the evaporator water flow rate is not to be reduced below 60% of the design flow, a value that is also recommended by chiller manufacturers (McQuay International 2005).

The evaporator water flow control strategy can be summarised as follows:

- Install a VSD on the evaporator water pump(s).
- Open all existing control valves in the evaporator water line.
- Permanently reduce the pump speed by setting the upper speed limit to correspond with the evaporator water design flow.
- Modulate the pump speed by controlling the evaporator water flow to maintain a specified chilled water dam level below 100% (PID control).
- Avoid degraded evaporator performance by setting the lower speed limit to correspond with 60% of the evaporator water design flow.

The strategy will therefore simply ensure that only enough water is chilled as required by the demand. This will lead to lower average cooling loads imposed on the chiller than previously as well as to lower evaporator pump energy consumption than before. The required water temperature and availability and thus the integrated cooling system cooling load are not expected to be affected.

4.3 Condenser flow control

Condenser water flow rates are usually kept fixed at design values in mine chillers, similar to the evaporator flows. However, the design thermal loads imposed on the condenser are rarely encountered. The theoretical heat exchange in the condenser is similar to that in the evaporator and is given by Equation 20 (Sonntag et al. 2003):

$$\dot{Q}_c = \dot{m}_w c_{pw}(T_{wo} - T_{wi}) = \dot{m}_r \Delta h_r \tag{20}$$

It can be seen that if the mass flow is kept at the design point, but the thermal load is lower than design, the temperature rise in the condenser water will also be lower than design. This is not necessarily bad, because a low average condenser water temperature improves the chiller COP since it lowers the condenser refrigerant pressure required. However, it is apparent that there is potential to save pumping energy by reducing the flow such that the temperature rise is at its design point. This is of particular interest when considering that chiller cooling loads (and hence also condenser thermal loads) will be reduced and modulated regularly by the proposed evaporator flow strategy.

A further energy saving opportunity in the condenser water circuit is apparent from the popular mine practice of using valves to throttle and maintain a constant condenser flow. It is proposed to open all existing flow control valves and install a VSD on the condenser water pump(s). The pump motor speed is then continuously controlled by means of a PID control loop so that the design water temperature difference is maintained across the condenser. The strategy block diagram is shown schematically in Figure 21.

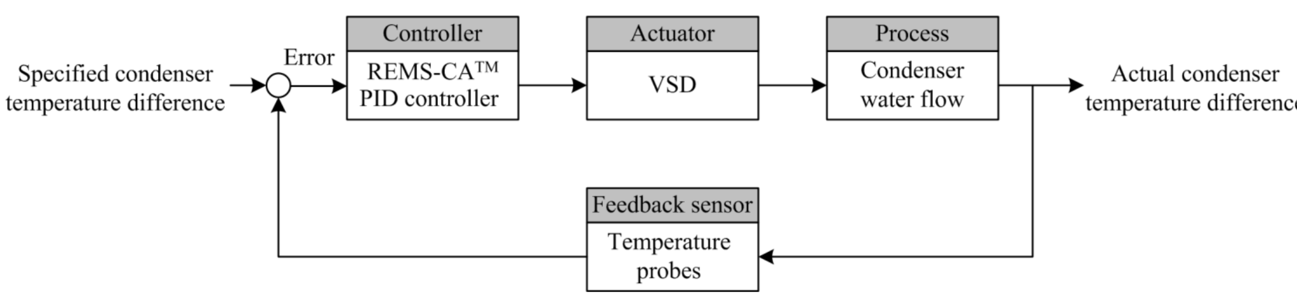

Figure 21 Block diagram of condenser water flow control

The base energy savings resulting from opening throttle valves are the same as discussed for the evaporator flow control. However, the effects of varying condenser water flow below design conditions must be carefully considered.

Most manufacturers warn against permanently reducing the water flow to a constant value below design flow. For a given cooling load the rejected heat in the condenser remains constant and therefore the water temperature difference across the condenser will permanently increase. This results in an increased compressor discharge pressure, which increases compressor electrical energy usage and lowers the COP correspondingly (McQuay International 2005).

The preferred strategy is to adapt to changing chiller loads by maintaining the design condenser temperature difference when varying the water flow, as recommended by Yu and Chan (2010) and Gordon et al. (2000). The condenser cooling tower is typically designed to be able to handle the condenser design water temperature rise. The design temperature difference is therefore expected to be maintained, although the absolute values of inlet and outlet water temperatures will vary in proportion to ambient conditions affecting the cooling tower performance.

It has been estimated that every 1 ºC increase in condenser inlet water temperature results in a 3% increase in chiller compressor power (Arndt 2000). However, condenser water pumps on large cooling systems are generally driven by high powered electric motors. Consider a hypothetical but typical case where the design condenser water temperature increase is 5 ºC but it is usually only about 3 ºC at partial loads. To increase the temperature rise to 5 ºC, a 40% water flow reduction is required. From Figure 4 the pump power reduction is estimated at about 70%. The mentioned estimate implies that the chiller compressor energy will increase by 6%. The actual savings will depend on system specifications, but for a typical chiller with a 200 kW pump and a 1 000 kW compressor a net saving of 80 kW will be realised. It is thus proposed that the water pump energy savings will outweigh minor reductions in chiller performance.

For the same reasons as discussed for the evaporator flow control, the condenser flow rate is not to be decreased below 60% of the design flow, a value that is recommended by chiller plant manufacturers (McQuay International 2005). In addition to this, the lower flow and pressure limit of the condenser cooling tower must be considered.

Most manufacturers recommend that the water flow not be reduced below 80% of the design point since this will lead to uneven fill wetting and hence increased rates of scaling and low efficiencies (Van Goor 2012). During commissioning, it must thus be observed at which flow the spray patterns are affected adversely and the lower limit be set accordingly.

The condenser water flow control strategy can be summarised as follows:

- Install a VSD on the condenser water pump(s).
- Open all existing valves in the condenser water line.
- Permanently reduce the pump speed by setting the upper speed limit to correspond with the condenser water design flow.
- Modulate the pump speed by controlling the condenser water flow to maintain the design water temperature difference across the condenser (PID control).
- Avoid degraded condenser and condenser cooling tower performance by setting the lower speed limit to correspond with either 60% of the condenser water design flow or the point at which cooling tower spray patterns start being adversely affected.

The strategy will thus simply ensure that the design condenser water temperature rise is maintained when the thermal load is below design point due to evaporator cooling load variations. This will lead to lower condenser pump energy consumption than before, outweighing a slight increase in chiller energy consumption.

4.4 Bulk air cooler flow control

The mine cooling system service delivery requirement applicable to the BAC is that the ventilation air underground must always be maintained at specified conditions. The wet-bulb temperature of the cool ventilation air entering the shaft is typically about 8 ºC. This will usually ensure and maintain the maximum allowable underground wet-bulb temperature at or below 27.5 ºC (Vosloo et al. 2012). The main constraint when developing a variable BAC flow strategy is therefore to keep the maximum wet-bulb temperature in underground working areas at or below this value.

The first energy saving opportunity in the BAC water circuit is once again presented by the mine practice of using valves to throttle the BAC flow continuously at design flow. The second opportunity is presented by the fact that BACs are usually designed to supply the required ventilation air temperature for worst-case summer ambient conditions. Ambient conditions that are lower than this are most commonly encountered during daily BAC operations (McPherson 1993). This means that for large portions of a day most BACs supply ventilation air at wet-bulb temperatures much lower than actually necessary. A third opportunity for energy savings relates to mines operating the BAC return water pumps without necessarily considering the level of the BAC drainage dam.

It is proposed to open all existing flow control valves and install VSDs on the BAC supply water pumps. The supply water pump speed is continuously controlled in direct proportion to the ambient air psychrometric conditions by means of feed-forward control, specified within design limitations. This will ensure that the ventilation air demand will be met without over-cooling.

VSDs are also to be installed on the return water pumps. The pump speed is continuously controlled by means of PID control logic so that a specified BAC drainage dam level is maintained. The strategy block diagram is shown schematically in Figure 22.

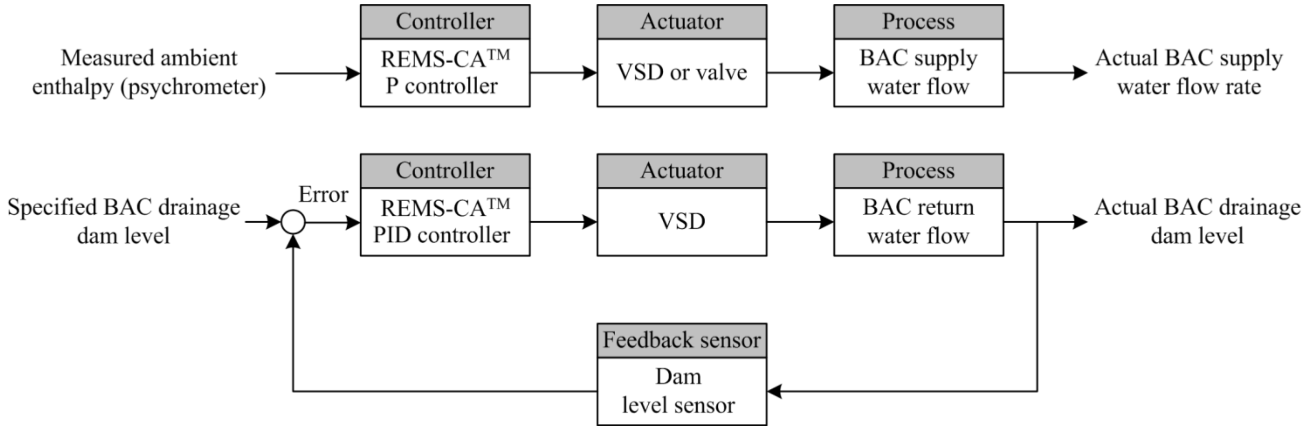

Figure 22 Block diagram of BAC water flow control

The control input parameter for the BAC supply water flow is to be ambient enthalpy. The air enthalpy is calculated in real-time, using air pressure and wet- and dry-bulb temperatures obtained from a compact digital psychrometer. An air enthalpy increase, at a constant dry-bulb temperature, signifies an increase in relative humidity (McPherson 1993). More water flow is required and the valves will be commanded to open proportionally. When the enthalpy decreases, the reverse process takes place. By using enthalpy as control parameter the ambient psychrometric conditions are reflected. This makes it possible to control the supply of ventilation air requirements according to the prevailing ambient conditions.

The control limits of the BAC supply water must be determined precisely for a specific system upon commissioning. The upper limit of the flow should be the BAC design water flow and should correspond with design ambient enthalpy. The lower limit of the flow should be zero and should correspond to the point where ambient conditions equal the required conditions in the shaft. The performance of the BAC should also be taken into account in that there must be sufficient water pressure and flow to prevent the fill material from fouling.

The BAC flow control strategy is not based on feedback control logic by using the BAC outlet conditions as inputs, as would initially be expected. This is because it has been found that on most mines instruments that are installed in the shaft area are often neglected as far as maintenance is concerned. The efforts required to physically reach the BAC outlet area in the shaft usually require a temporary shaft shutdown.

On recommendation of various mine instrumentation personnel, it was therefore decided to base the BAC flow control strategy on simple forward-loop control. A feedback strategy with the outlet conditions as set points would be more accurate, but if the forward-loop set point limits are correlated suitably well to the achieved outlet conditions upon commissioning, this strategy will be acceptably accurate under given circumstances.

The base energy savings resulting from opening throttle valves are the same as discussed for the evaporator flow control. Further pump energy savings are expected when the BAC supply water flow rate is reduced at times when ambient enthalpy is below design conditions.

Indirect energy savings are also expected from the overall reduction chilled water demand from the chilled water dam. The extent of this saving will depend on ambient conditions, but significant reductions are expected in the daily cooling demand of the chillers. This will translate into reductions in electrical energy requirements, especially when considering that the evaporator water flow control will now enable the chilled water supply to be matched to the demand.

Return pump energy savings will be realised from reduced water flow requirements when the BAC drainage dam level is kept constant. The extent of these savings depends on how much the BAC supply water is reduced, because this is the same volume of water that must be returned to the pre-cooling dam.

It should be noted that on many mine cooling systems the BACs are gravity fed from the chilled water dam. In such cases, the strategy will be adapted to include electrically actuated control valves in the supply water line in conjunction with the VSDs on the return water pumps. In this way the BAC supply water will still be reduced according to ambient conditions as described previously.

The BAC water flow control strategy can be summarised as follows:

- Install a VSD (or control valve when the BAC is gravity fed) on the BAC supply water pump(s).
- Install a VSD on the BAC return water pump(s).
- Open all existing valves in the BAC supply and return water lines.
- Permanently reduce the pump speeds by setting the upper speed limits to correspond with the design water flows.
- Modulate the BAC supply water flow in direct proportion to the ambient air enthalpy, supplying the design flow at the design ambient conditions and no flow when the ambient conditions equal the shaft requirements (feed-forward control).
- Modulate the BAC return pump speed to maintain a specified BAC drainage dam level (PID control).
- Avoid degraded BAC performance by setting the lower speed limit to correspond with the point at which BAC spray patterns start being adversely affected (if applicable).

The strategy therefore simply ensures that the shaft ventilation air requirements are met in proportion to ambient conditions, without oversupplying the wet-bulb temperature demand. Water pump electrical energy consumption as well as daily cooling demands on the chiller will be reduced in the process.

4.5 Pre-cooling tower flow control

The evaporator flow control strategy pumps water from the pre-cooling dam to maintain a set chilled water dam level. The BAC return flow strategy pumps water into the pre-cooling dam and maintains a set BAC drainage dam level. It follows that, to maintain equilibrium of all water mass flows in the system, the pre-cooling dam level should be maintained by modulating the only remaining controllable flow, namely the pre-cooling tower supply water. In this way the water supply and demand of the pre-cooling dam are balanced out in steady state, while also realising pump energy consumption.

It is proposed to open all existing flow control valves and install VSDs on the pre-cooling supply water pumps. The pump speed is then continuously controlled by means of PID control logic so that a specified pre-cooling dam level is maintained. The strategy block diagram is shown schematically in Figure 23.

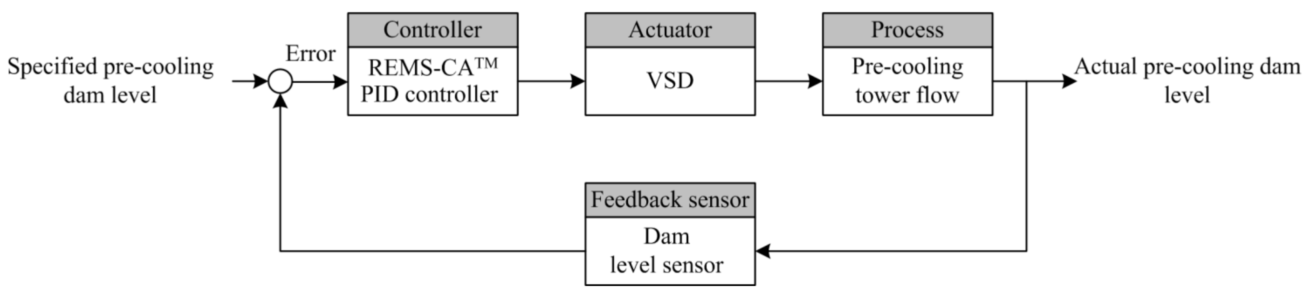

Figure 23 Block diagram of pre-cooling water flow control

It is worth noting that, for given ambient conditions, the pre-cooling tower outlet water temperature might reduce somewhat if the water flow is reduced from design point (depending on the ambient wet-bulb temperature and achievable cooling tower approach value). If the average pre-cooling dam temperature decreases, so does the chiller cooling load. The worst case scenario would be for the pre-cooling pumps to operate at design flows if, for example, the dam level is sufficiently low. Achieved water temperatures will in this case just be equal to what they would have been without any VSD intervention for the same ambient condition.

The only dam in the integrated cooling system for which it is not possible to implement level control is the hot water storage dam. However, if all flow rates are balanced properly as proposed by the four control strategies, the daily average inflow into the hot dam should be approximately equal to the chilled dam outflow. This means that, in steady state, all flows and dam levels should be balanced by the operation of the pump VSDs.

The pre-cooling water flow control strategy can be summarised as follows:

- Install a VSD on the pre-cooling tower supply water pump(s).
- Open all existing valves in the pre-cooling tower supply water line.
- Permanently reduce the pump speeds by setting the upper speed limits to correspond with the design water flows.
- Modulate the pump speed to maintain a specified pre-cooling dam level (PID control).
- Avoid degraded pre-cooling tower performance by setting the lower speed limit to correspond with the point at which cooling tower spray patterns start being adversely affected.

The strategy thus simply ensures that the mass balance of the pre-cooling tower dam is in equilibrium, while simultaneously lowering pump energy consumption and maintaining or improving pre-cooling dam water temperatures.

4.6 Conclusion

Based on the findings of Chapter 3 and research budget limitations, it was decided to only implement VSDs on pumps of large mine cooling systems. To successfully realise pump VSD energy savings, a new variable water flow strategy was proposed. The strategy consists of four generic substrategies, one for each of the main pump sets usually found on these systems. Each strategy aims at modulating its pump speed so that its specific demand or requirement is matched in the simplest way possible.

Evaporator water flow control was proposed and based on modulating evaporator water pump speeds to maintain chilled water dam levels, while adhering to chiller constraints. Condenser water flow control was shown to be based on modulating condenser water pump speeds to adapt to the changing thermal load by keeping the design condenser water temperature rise constant. BAC water flow control was proposed to be based on modulating the supply water flow in direct proportion to the ambient air enthalpy. The return water flow is then controlled by maintaining the BAC drainage dam level. Finally, pre-cooling tower supply flow rates are to be controlled so that a set pre-cooling dam level is maintained.

The strategies were discussed in broad terms since the basic control principles will remain generic when applied to various mine cooling systems. However, each system has its own unique specification and will therefore require certain adjustments and customisations. These adjustments as well as system-specific control details (such as PID gain constants) will therefore be discussed when describing the specific applications to case studies in later chapters.

It was discussed how each strategy is predicted to influence the performance and energy consumption of the relevant subsystem. The strategies are in essence very simple and are merely aimed at matching the chilled water and air demand with the supply without any oversupply. If this is implemented efficiently, the results will include reduced pump and chiller energy consumption, unchanged service delivery and system performance and the elimination of previously-used inefficient operational methods.