CHAPTER 5. A NEW VARIABLE WATER FLOW ENERGY MANAGEMENT SYSTEM

5.1 Introduction

Previous chapters indicated that there is a need to implement VSDs on mine cooling systems and that pumps seem to be the most viable starting point for a new DSM strategy. A simple variable water flow strategy, consisting of four substrategies, was subsequently proposed according to which the pump speeds of the various subsystems will be controlled. It is sensible that these variable-flow strategies should be integrated and effectively controlled from a central point to enable the collective energy management of the cooling system pumps. Chapter 2.7 also showed that there is a need for such a system to function in real-time and that it should be simple, user-friendly and robust, typically utilising a hierarchical control architecture in an integrated manner.

New energy management software called Real-time Energy Management System for Cooling Auxiliaries (REMS-CA™) was therefore developed with the financial support of HVACI (2012) to implement, control, monitor and report savings of the outlined strategies. The developed system is an integral part of the new DSM strategy addressing the research problem of developing an integrated variable water flow strategy for energy savings on large cooling systems. An overview of the integrated energy management system is discussed in this chapter, including descriptions of its system architecture, functional specification, control, integration, monitoring and reporting capabilities.

The focus of the system is a generic systems approach to energy efficiency and integrated energy management. Key features include a robust supervisory and functional specification, a simple optimisation and hierarchical control system, an easy-to-use interactive monitoring platform and an automatic reporting system.

The programmed source code of the energy management system is not included in this thesis due to confidentiality reasons. The description of the energy management forms part of Annexure C.1 (Du Plessis et al. 2013b).

5.1 System architecture

It was shown in Figure 14 that the amount of system components that need to be controlled and integrated increase at device level of a typical industrial automation hierarchy. It was then shown that a popular approach to implement complete system control without having an excessive number of inputs and outputs is to use hierarchical control such as shown in Figure 15. The proposed variable-flow strategies need to be handled in a similar manner because there are four substrategies, each implemented on different subsystems that will typically have different PLCs controlling them. The new energy management system was therefore developed on the principle of hierarchical cascade control. The energy management system integrates with existing mine communication networks as shown in Figure 24 (Du Plessis et al. 2013b).

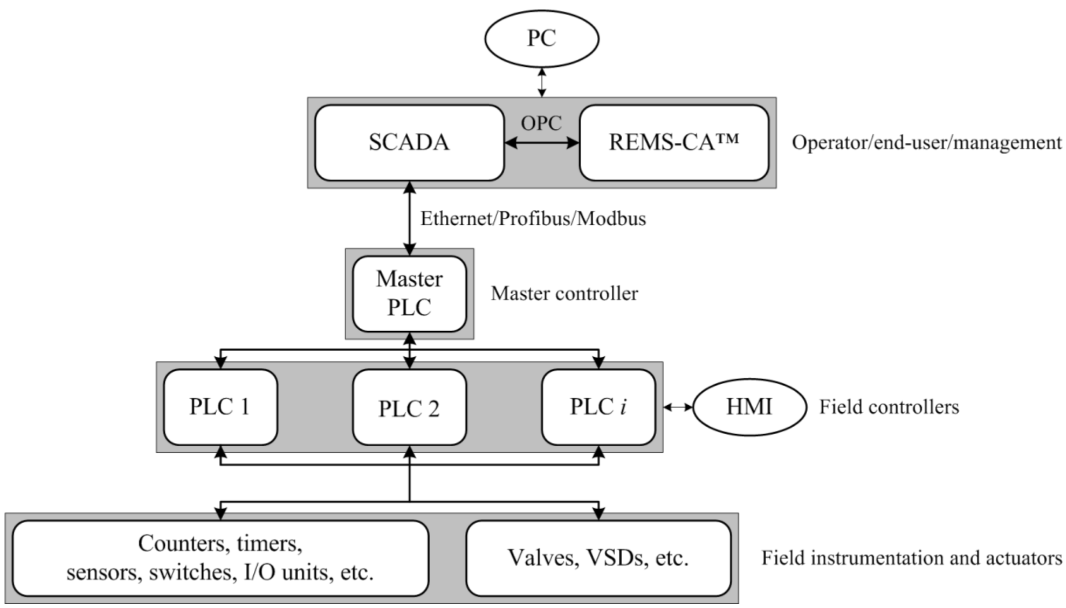

Figure 24 Hierarchical control system architecture of REMS-CA^{TM} (Reprinted from *A versatile energy management system for large integrated cooling systems*, Du Plessis G.E., Liebenberg L., Mathews E.H., Du Plessis J.N., Energy Conversion and Management, 66, 312-325, Copyright (2013), with permission from Elsevier)

Figure 24 shows that the system architecture involves inner control loops managed by a network of local PLCs and an outer control loop managed by the mine SCADA system. This ensures complete control and monitoring of the entire PLC network. The REMS-CA^{TM} server communicates with the mine SCADA client via the OPC protocol (OPC 2012). This protocol enables the real-time exchange of data between two independent platforms.

It therefore ensures that the energy management system can write and read values to and from the master PLC and hence interact with all field instrumentation and actuators. The OPC connection enables the system to be integrated to any mine SCADA and thereby ensures a generic energy management tool.

The information flux between the SCADA and PLCs is typically enabled through an Ethernet, Profibus or Modbus network. Such networks are well-proven and industrial standards and therefore permit simple accessibility to all subsystems.

The energy management system server is accessed through an interactive user interface, usually viewed from a personal computer (PC) that is located at and connected to the SCADA. This allows the user to monitor and control the energy management system in conjunction with the existing SCADA system. Field controllers also have human-machine interfaces (HMIs) to enable preferential control in case of emergencies.

The hierarchical cascade control system architecture of REMS-CA™ allows the system to receive data input from the entire integrated cooling system and also to send control inputs to all the controllable equipment from a central point. It simplifies the integrated energy management process greatly because only a single connection is made to access the control network. It therefore facilitates the system to be very simple, robust and practical in its operations.

5.3 Functional specification

Before the control implementation and integration methods of the developed energy management system can be discussed, the functional specifications must be clarified. This includes an overview of the inputs and outputs of the system and a description of the network communication paths that must be set up in the existing control network to allow the intended functionality of REMS-CA™.

Figure 25 (Du Plessis et al. 2013b) shows the key functionalities of REMS-CA™ as an energy manager. After the system is customised for a specific cooling system via a user friendly visual editor suite, preferences can be provided on the user interface. Such preferences typically include allowable control limits of equipment and specific subsystem set points to ensure that service delivery requirements are met. The system uses these preferences along with real-time system feedback from relevant inputs to facilitate four key functional outputs. These high-level outputs are real-time monitoring of energy usage and all system parameters, real-time optimisation and control of cooling system auxiliary equipment according to the new variable-flow strategies and the automatic daily, weekly and monthly reporting of energy consumption.

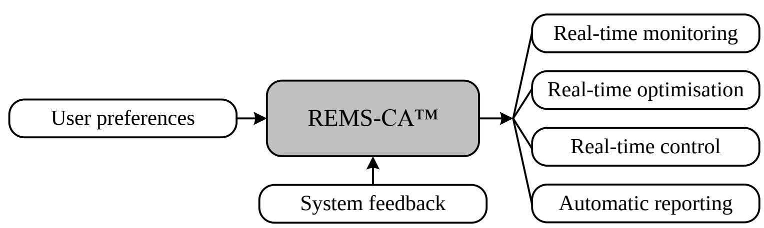

Figure 25 Key functionalities of REMS-CA™ (Reprinted from *A versatile energy management system for large integrated cooling systems*, Du Plessis G.E., Liebenberg L., Mathews E.H., Du Plessis J.N., Energy Conversion and Management, 66, 312-325, Copyright (2013), with permission from Elsevier)

A robust specification for the various communication and control scenarios between REMS-CA™, the SCADA, PLCs and cooling system is important. Redundancy must be built into the computerised management system to ensure that it is practical for implementation as an automatic plant controller. This means that any control scenario must be suitably handled. It follows that relevant programming and software development additions must be made on existing SCADA and PLC networks concerning the permission for REMS-CA™ to control and the fail-safe handling of control losses.

Figure 26 (Du Plessis et al. 2013b) shows the communication and control paths required to ensure the robust connection of REMS-CA™ to existing cooling system networks.

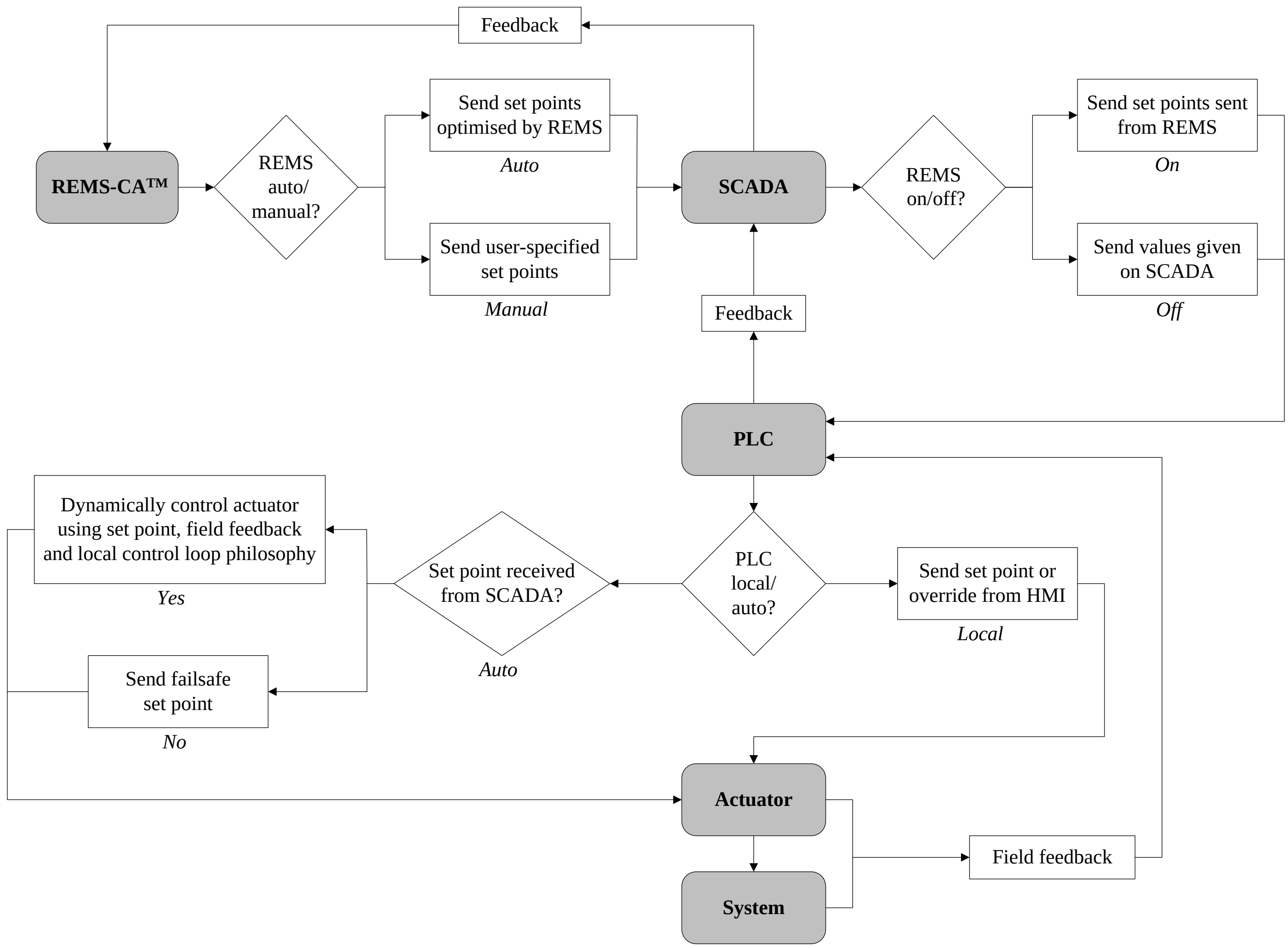

Figure 26 Control network communication specifications of REMS-CA™ (Reprinted from *A versatile energy management system for large integrated cooling systems*, Du Plessis G.E., Liebenberg L., Mathews E.H., Du Plessis J.N., Energy Conversion and Management, 66, 312-325, Copyright (2013), with permission from Elsevier)

Figure 26 indicates that REMS-CA™ has automatic and manual control modes. This allows the user to choose between automatic set point optimisation and manual set point overriding or adjustment. The SCADA software must be extended to include the option of providing REMS-CA™ with control permission. This allows the SCADA operator to choose whether the relevant set points are controlled or given by REMS-CA™, or whether the set points fixed on the SCADA will be used.

PLCs can generally be controlled locally from the HMI or automatically from the central SCADA. This means that no alteration regarding control permission options is necessary on the PLC. If local control is selected, the set points can be overridden (typically in an emergency situation). If automatic control is selected, the PLC receives a set point value from the SCADA (whether this originated from REMS-CA^{TM} or the SCADA itself) and implements it accordingly on the relevant field actuators, such as VSDs.

System or field feedback is provided in industrial automation in the form of process variable readings taken in real-time by a variety of field instruments and sensors such as temperature probes, pressure sensors, tachometers, etc. These readings are sampled and updated frequently, usually at rates of 1 to 20 times per second. The real-time readings are sent back to the PLC(s) from where it is relayed directly to the SCADA, and ultimately also to REMS-CA^{TM} in this case. The same system feedback is therefore simultaneously received and read by the PLC, SCADA and REMS-CA^{TM}.

Figure 26 further illustrates the concept of hierarchical control by REMS-CA^{TM}. It can be seen that the only output values from REMS-CA^{TM} are set point values, or control objectives, that must be maintained. These are then relayed via the SCADA to the PLC. The PLC then takes the set points and implements the relevant control philosophy as discussed in the previous chapter. It does so dynamically, typically using PID control logic and the feedback received from the controllable parameters. The PLC will continue implementing the control loop until such time when the set point is changed by REMS-CA^{TM}. A failsafe set point is also programmed into the PLC to use in the case of communication loss with the SCADA.

REMS-CA^{TM} can merely relay a user-defined fixed set point (manual mode) or it can select an optimal set point value for given circumstances (automatic mode). The ways in which this is done are discussed in the next section. Either way, the output of the REMS-CA^{TM} server to the SCADA is presented only by set points, while the energy management system control philosophies are implemented dynamically by the PLCs.

The described hierarchical control structure has two primary advantages. First, the computation time and complexity required from the central REMS-CA^{TM} server is minimised as it must only integrate and optimally select set points in addition to its reporting and monitoring functions.

Second, the reliability of the integrated energy management system is improved. In the event of the REMS-CA™ server or its OPC connection malfunctioning, the developed variable-flow strategies will still be dynamically controlled by the PLCs, using the most recently received set points.

The flow chart in Figure 26 indicates that the various options of the control loop are specified so that control will never be relinquished. Intended performance can be expected when all PLCs are in automatic inner control mode, control permission is given by the SCADA and REMS-CA™ is in automatic outer control mode. In addition to the communication requirements as specified, a backup REMS-CA™ server ensures automatic fail-over transfer to a mirrored platform.

It can be concluded that the functionality of REMS-CA™ involves the use of user input and system feedback to monitor, optimally control and report savings of various cooling subsystems. The hierarchical control functionality is specified such that control will never be relinquished. Set points are sent (whether they are optimised or fixed) to local PLCs to implement using local subsystem PID logic. Redundancy is therefore built into the energy management system and it can be considered robust and simple for practical application to mine cooling systems.

5.4 Implementation and integration

The main purpose of REMS-CA™ is to implement the variable-flow control strategies described in Chapter 4. The system architecture and functional specification of the system as a robust hierarchical controller have been discussed. This section provides an overview of the layout and methods of strategy implementation and integration.

The user accesses, monitors and controls REMS-CA™ via a user platform displayed as an application on the system server. All the functions of the energy management system are centrally controlled from this platform, given that the SCADA and PLC permissions and programming have been developed as described in the previous section. The platform has been designed to be entirely generic so as to allow for simple application to different cooling systems. The layout of any specific site is then created by adding and connecting generic cooling system equipment, controllers and other components. An example of the generic components available when customising the platform is shown in Figure 27.

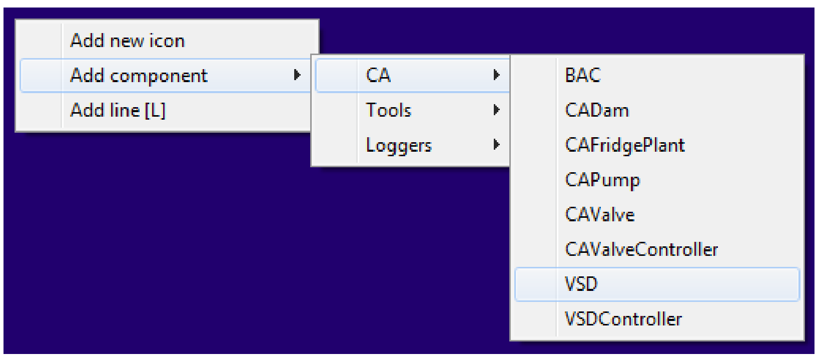

Figure 27 Customised platform development in REMS-CA™

Figure 27 illustrates how the generic cooling system components are selected. The relevant icons are then arranged and linked on the screen to reflect the process layout of the specific cooling system. Then the specifications, control parameters and process variables from the SCADA and PLCs are added and edited for each specific component.

The completed REMS-CA™ platform typically consists of a main page on which the entire integrated cooling system is displayed for supervisory monitoring as well as a series of control pages on which the subsystems are displayed and control set points edited. A logging page is also added to show real-time graphical displays of key parameters. Examples of the main page and a control page are shown in Figures 28 and 29, respectively. Table 12 lists the various key features as pointed out in the figures.

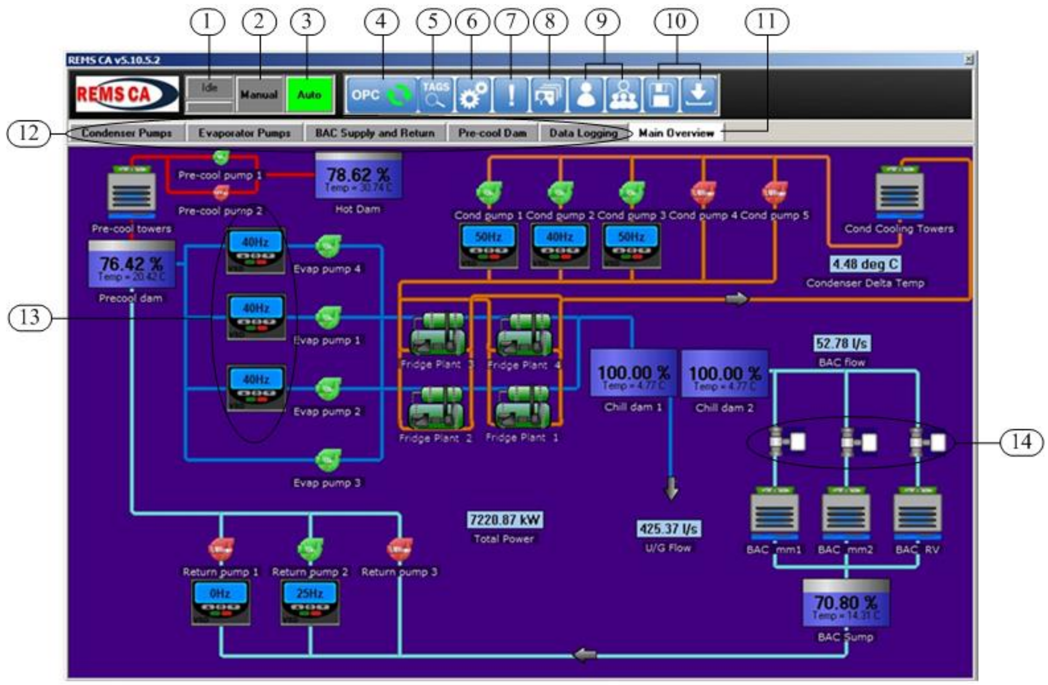

Figure 28 Example of a main page in REMS-CA™

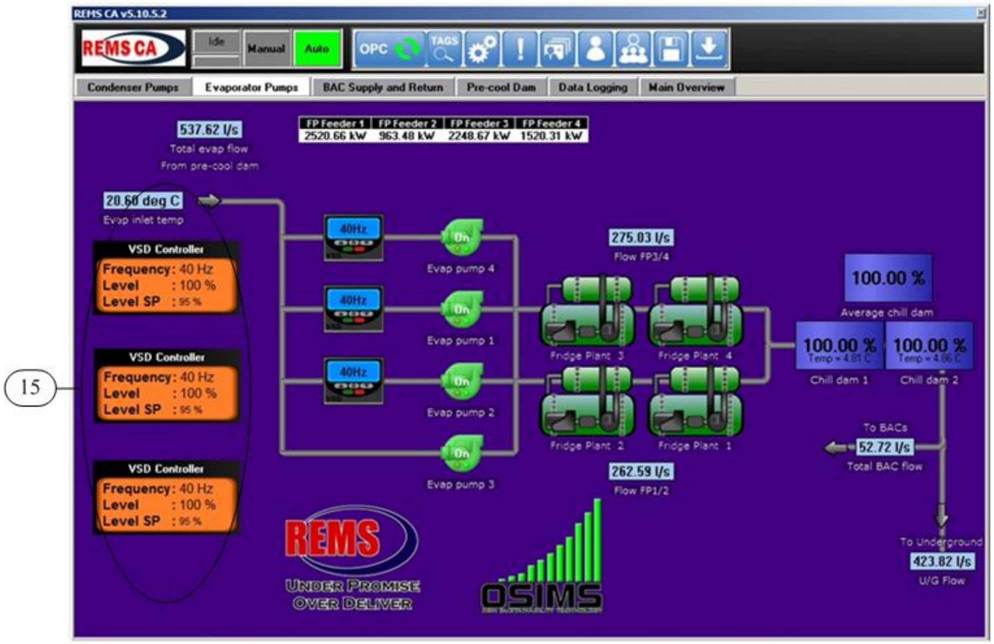

Figure 29 Example of a control page in REMS-CA™

Table 12 Key platform components of REMS-CA™

Number	Component
1	Idle mode selector
2	Manual mode selector
3	Auto mode selector
4	OPC connection settings
5	SCADA tag browser
6	General settings
7	Alarm settings
8	Contact details
9	User manager
10	Platform file manager
11	Main page tab
12	Control and logging page tab(s)
13	VSD component
14	Valve component
15	Generic VSD controllers

Figure 28 shows that the platform user interface is generally colourful, intuitive and easy to use, as recommended by Avouris (2001). Selecting the *Idle* mode enables the offline editing of any component (with relevant passwords), while the *Manual* and *Auto* modes enable the manual adjustment or the automatic optimisation of subsystem set points, respectively. Settings for the OPC connection, alarm signals and general preferences are easily accessed. The global list of all system tags (PLC addresses of instrumentation and control input and output signals) can be viewed conveniently.

The controllable features, such as VSDs and control valves, are indicated as separate components. Control pages are navigated by separate tabs on the platform and give more controllable detail of any specific subsystem. For example, Figure 29 shows the evaporator pumps and includes three generic VSD controllers, one for each VSD.

The variable-flow strategies are implemented directly by the generic VSD and valve controller components such as the ones shown in Figure 29. These components have been designed in such a way that programming and editing of its control is very simple and intuitive. When the controller is double-clicked, a control settings interface is displayed in which all the control preferences can be edited. The control interface of a generic VSD controller that has been customised for evaporator flow control is shown in Figure 30 (Du Plessis et al. 2013b).

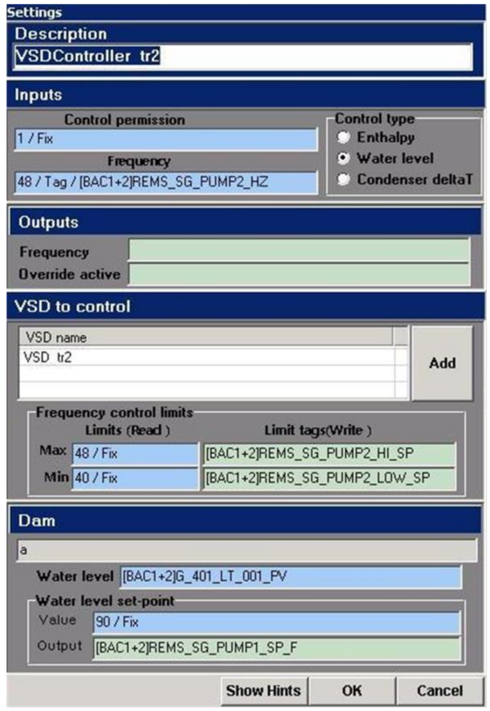

Figure 30 Evaporator, BAC drainage dam and pre-cooling tower control interface in REMS-CA™ (Reprinted from *A versatile energy management system for large integrated cooling systems*, Du Plessis G.E., Liebenberg L., Mathews E.H., Du Plessis J.N., Energy Conversion and Management, 66, 312-325, Copyright (2013), with permission from Elsevier)

Figure 30 shows that *Water level* has been selected as the control strategy, as applicable to the variable water flow strategy for evaporator, pre-cooling or BAC drainage dam pumps. The VSD or VSDs to which these inputs must be sent are selected from a list displaying all VSDs in the integrated system. Frequency limits are entered, as determined during commissioning, and PLC addresses (or *tags*) are selected for these limits. Similarly, the specific dam that must be controlled is selected, its level set point is entered and the relevant PLC address is selected.

The controllers that implement the condenser and BAC flow strategies are comparable to the one for water level control. The main differences are in the selection of *Condenser delta T* and *Enthalpy* as control parameters, as shown in Figures 31 and 32 respectively.

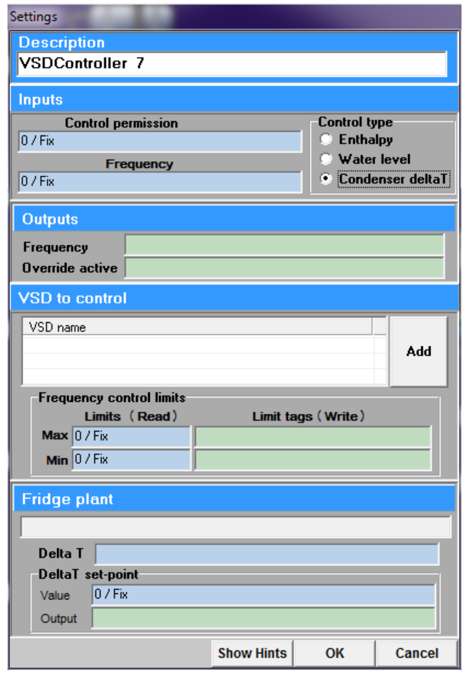

Figure 31 Condenser control interface in REMS-CA^{TM}

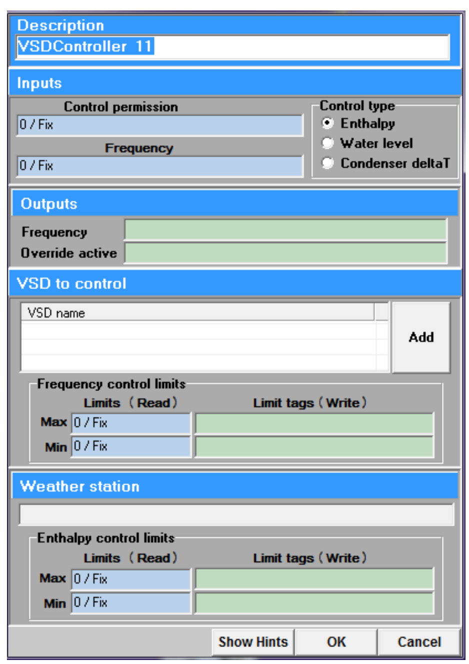

Figure 32 BAC control interface in REMS-CA^{TM}

Generic controllers are also available for valves and are set up in the same way, except that valve position limits are specified instead of VSD frequency limits.

It will sometimes be required to adjust the VSD or valve set points manually and fix them for a period of time, depending on operating conditions and circumstances. To facilitate this, it is possible to double-click the VSD or valve component (as shown in Figure 28) when in *Manual* mode. An interface will appear that shows the present readings of key VSD parameters. It is possible to edit the frequency directly on this interface to override the control loop, given that the user has permission. An example of this interface is given in Figure 33.

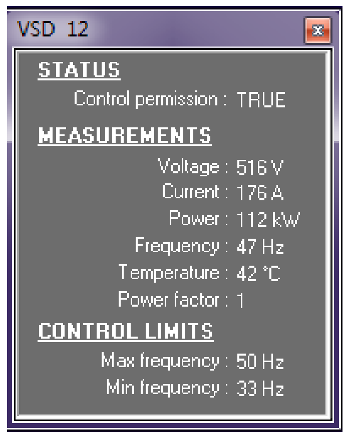

Figure 33 Manual VSD override and display interface in REMS-CA™

REMS-CA™ integrates the components and system *tags* in a simple manner to manage the energy usage of the system. The inputs that are updated in real-time are all the various system parameters that are viewed, used for control and logged such as temperatures, flows, energy consumption, etc. The outputs to the PLCs are the various control set points, either fixed as defined by the user, or optimised in real-time when in *Auto* mode. The relevant PLCs are programmed to implement the control logic described in Chapter 4. In this way the integrated energy management solution is very stable and robust and also very simple to use.

Figure 34 (Du Plessis et al. 2013b) presents a schematic summary of the integrated control and optimisation process of typical generic controllers within REMS-CA™ as applied to the generic mine cooling system shown in Figure 19. Five examples of local PLCs are set up to control the variable water flow strategies as discussed in Chapter 4. As an example, the automatic selection of an optimal frequency set point is shown for the first controller.

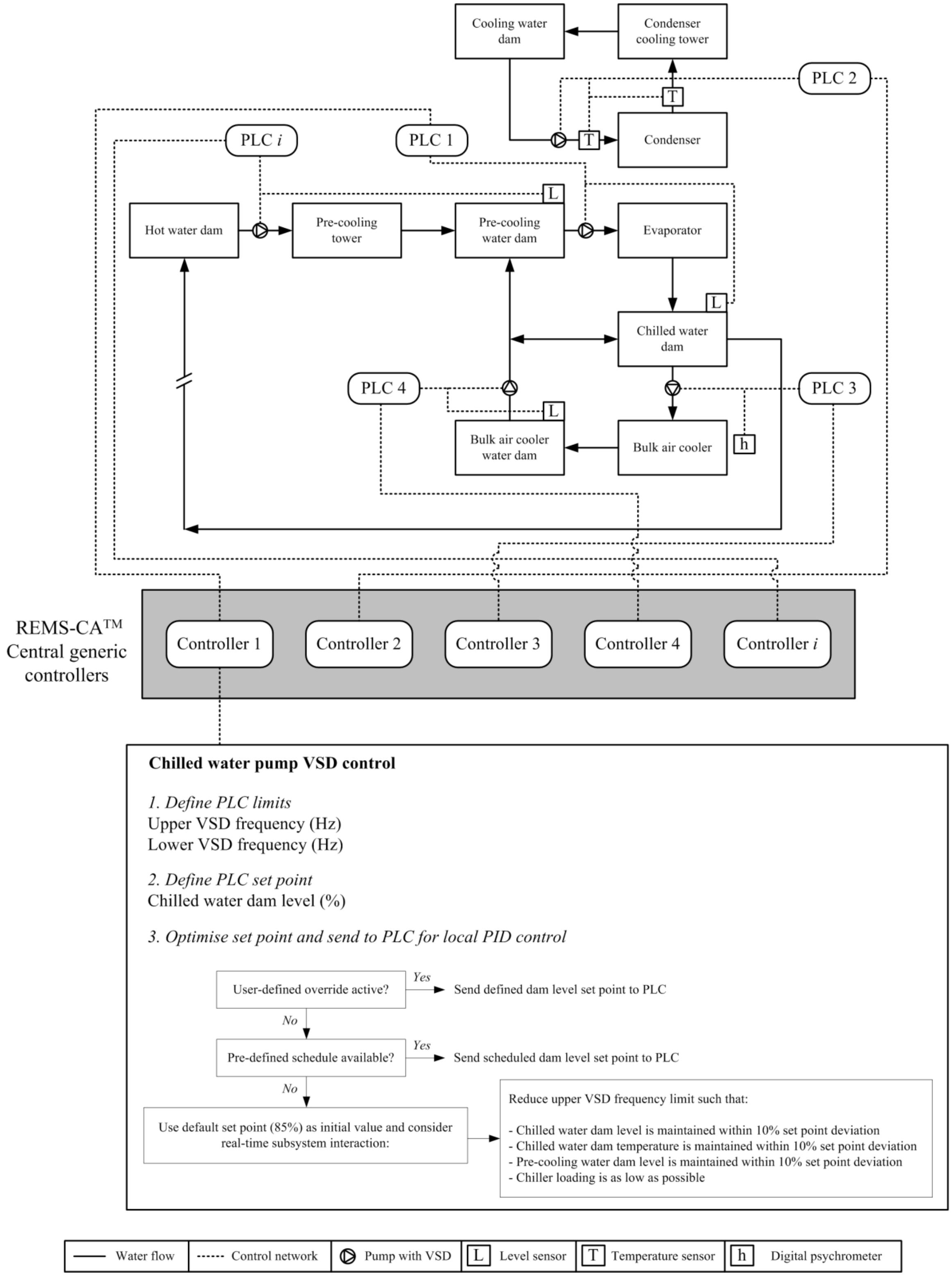

Figure 34 Control and integration of generic controllers in REMS-CA™ (Reprinted from *A versatile energy management system for large integrated cooling systems*, Du Plessis G.E., Liebenberg L., Mathews E.H., Du Plessis J.N., Energy Conversion and Management, 66, 312-325, Copyright (2013), with permission from Elsevier)

Figure 34 shows that Controller 1 is set up to control the chilled water pump speed by means of a VSD to maintain the chilled water dam level. The user first defines VSD frequency control limits and the type of set point (in this case the dam level), as shown in Figure 30. If a defined override frequency or a scheduled set of pre-defined set points are not available, the system continually minimises the upper frequency limit for minimum energy usage.

In this case, the objective is to ensure that the chiller loading is as low as possible while maintaining 10% deviation of the required chilled water temperature, chilled water dam level and pre-cooling dam level at all times. REMS-CA™ selects the upper VSD frequency limit to be equal to the lower limit initially since this is the ideal case for minimum pump energy consumption and chiller loading. It then checks whether the dam levels on either side of the pump as well as the chilled water temperature are within 10% of the set point. If they are, it maintains the existing upper frequency limit. If not, it increases the upper limit by 0.1 Hz. In this way the system ensures that the PID control loop performed by the PLC has an upper pump frequency limit that is as low as possible while remaining within safe operating conditions.

The method of changing the upper frequency limit for the condenser, BAC and pre-cooling tower strategies is implemented by the energy management system analogously to the example shown. In each case the critical system parameters directly influenced by the VSD under consideration are checked to remain within specified limits (typically the dam parameters before and after the relevant pump).

The developed energy management system therefore allows for simple implementation of the developed variable-flow strategies on subsystems, while considering the real-time interaction with other subsystems. An advantage of the outer-loop controller functions in the energy management system is that a large number of subsystems can be optimally controlled in an integrated manner without increased computational cost. Furthermore, the generic design of the controllers allows adaptability to various mine cooling system layouts such as shown in Figure 6. Electrical energy of integrated cooling systems on different sites can thus be optimally managed in real-time by using the same basic energy management tool, customised for each individual plant by using the simple component tools and controllers discussed.

5.5 Monitoring and reporting

An energy management system will not be complete without the functionality to monitor and track the performance of the system, specifically regarding its energy consumption. REMS-CA™ was therefore developed with the capabilities to monitor all systems and subsystems, including their energy consumption in real-time, to automatically log and enable trend extraction of any system parameter, to automatically alarm the user about pre-defined conditions, and to automatically create and send periodic energy consumption reports.

Supervisory energy management systems usually focus on a single primary end-user to monitor and control the system under consideration. To further develop this concept, the REMS-CA™ server is connected to a network that includes all stakeholders involved with the energy efficiency improvement of the cooling system. Such a network is shown in Figure 35 (Du Plessis et al. 2013b).

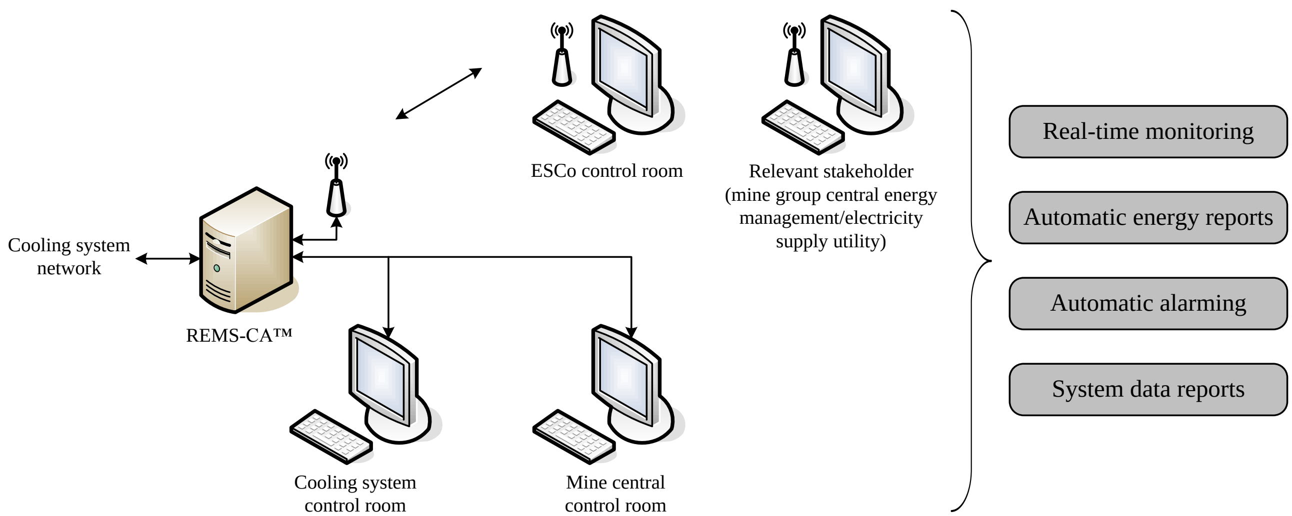

Figure 35 Integrated network for monitoring and reporting (Reprinted from *A versatile energy management system for large integrated cooling systems*, Du Plessis G.E., Liebenberg L., Mathews E.H., Du Plessis J.N., Energy Conversion and Management, 66, 312-325, Copyright (2013), with permission from Elsevier)

Figure 35 shows that the local mine network is typically connected to display monitors both at the plant and at the central control room of the specific mine. A wireless router further enables the remote connection to external locations such as the control rooms of the Energy Services Company (ESCO) responsible for implementation, mine group energy management or electricity supply utility.

The system enables the real-time monitoring function and usage reports to be available to an integrated network of interested parties. This ensures complete energy management by means of a top-down approach since energy-conscious performance is often of increased concern at managerial level.

It was shown in Chapter 2.7 that the monitoring function of an energy management tool should not only indicate important parameters in real-time, it should preferably do so in a visually appealing manner. The layout and integrated operation of the system and any energy efficient interventions should be clearly visible and easy to follow.

Real-time supervisory monitoring is made available in REMS-CA™ through the set of customised pages on the platform screen. For example, the layout of the complete system and any subsystems can be viewed as shown in Figures 27 and 28. A further page dedicated to real-time visual representations of critical system parameter profiles is also available. An example of such a page is displayed in Figure 36 (Du Plessis et al. 2013b).

Figure 36 Example of a monitoring page in REMS-CA™ (Reprinted from *A versatile energy management system for large integrated cooling systems*, Du Plessis G.E., Liebenberg L., Mathews E.H., Du Plessis J.N., Energy Conversion and Management, 66, 312-325, Copyright (2013), with permission from Elsevier)

Figure 36 shows that various monitoring, statistical and graphical display tools are available to the user. Typical examples include the graphical tracking of daily power consumption of the overall cooling system or its subsystems, tracking of critical system parameters such as dam levels or temperatures and the real-time calculation of cost savings realised by the management system. These real-time profiles will immediately indicate the short-term performance of the system, its energy usage and its critical parameters. This function is important since it gives a better overview of the immediate historical performance, rather than only monitoring real-time values.

An automatic alarm system can also be set up to alert the user to abnormal energy usage, system performance or network-related issues. Alarms can be set up and fully customised through the alarm function (number 7 in Figure 27). For example, if the energy consumption of a specific subsystem exceeds a defined limit, an alarm signal and/or sound will be activated that tells the user to take immediate action. This functionality is important in an industrial environment where it is often found that SCADA operators and monitoring staff are relatively unskilled and do not always differentiate between acceptable and poor performance of systems.

Every system parameter is automatically logged (at a customised time interval) by REMS-CA™ and saved in organised *.csv* files for each day. Trends of any parameter can therefore be conveniently extracted from the server computer for any time period. It is often the case that operators or foremen want to quickly view a parameter trend for a specific time period without first extracting the raw data files and compiling their own graphs. To address this need, the customised trend profiles shown on the monitoring page (as in Figure 36) can be enlarged and that particular profile extended to customised starting and finishing dates and times. This is shown in Figure 37 by a sample power usage profile.

Figure 37 Enlarged system parameter profile trend in REMS-CA™

An automatic reporting and data backup capability supplements the monitoring function of REMS-CA™. This system uses the logged plant and power data to automatically create a customised document reporting the energy usage, energy and cost savings measured against pre-determined baselines, and recommended areas for improvement in the operation of the integrated cooling system. These reports are created on a daily, weekly and monthly basis. All reports, alarms and recommendations are available on the system itself or automatically sent via e-mail or mobile phone text messages.

It is important to note that all the developed monitoring and reporting tools are available to anyone who can access the REMS-CA™ server and platform with relevant security clearance. This includes all stakeholders listed in Figure 39. Energy managers, ESCO personnel and any relevant management staff can thus actively monitor and control the system remotely should they wish to. This is an important functionality to ensure sustained and integrated energy management of the DSM strategy.

It can be concluded that REMS-CA™ enables a wide range of users, on- and offsite, to monitor system parameters and power usage in real-time. The system layout is clearly presented in addition to a customised page with critical parameters shown as real-time graphs. Logged trends can easily and quickly be extracted for any parameter. Alarms can be set up to alert the user of any abnormal system parameter or energy usage. Automatic reports are also generated and sent periodically to track the energy and system performance of the DSM intervention implemented by REMS-CA^{TM}.

5.6 Conclusion

The variable water flow strategy developed in Chapter 4 needs to be integrated and implemented by a central energy management system. It was previously shown that there is a need for an integrated energy management system for large cooling systems that should function in real-time and is simple, user-friendly and robust, typically utilising a hierarchical control architecture in an integrated manner.

A novel energy management tool called REMS-CA^{TM} was subsequently developed to implement, control, monitor and report savings of the developed strategies. This system implements, controls, monitors and assesses the different variable water flow strategies in an integrated manner.

A hierarchical cascade control system architecture allows the sending and receiving of data from a central point. This simplifies the integrated energy management process because only a single OPC connection is made to access the SCADA and existing control network.

The system uses user input and system feedback to monitor, optimally control and report savings of various cooling subsystems. Set points are sent to local PLCs to implement using local subsystem PID logic defined by the variable-flow strategies described in Chapter 4. Redundancy and robustness ensure practical application to mine cooling systems.

The system is viewed and controlled from a customised user platform. VSD and valve controllers are set up for each control strategy and control limits and set points can be edited or overridden. The system can also minimise the upper VSD frequency in real-time so as to optimise the PID control loop for minimum energy usage. The generic design of controllers and system components allows adaptability to various mine cooling system layouts.

The system enables a wide range of users, on- and off-site, to monitor system parameters and power usage in real-time through a wireless network. Logged trends can easily and quickly be extracted for any parameter. Alarms can be set up to alert the user of any abnormal system parameter or energy usage. Automatic reports are also generated and sent periodically to track the energy and system performance.

It can be concluded that a suitably simple and robust energy management system (REMS-CA^{TM}) was developed to implement, control, monitor and assess the variable water flow strategies discussed in Chapter 4. Details such as exact layouts and PID control gains are site-specific and will be discussed accordingly in the relevant sections.

Before a full-scale implementation of the developed strategy and energy management system could be considered, its energy saving potential had to be demonstrated and its feasibility investigated. This was done by means of a simulation model and cost analysis and will be discussed in the next chapter.