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Work Domain Analysis and Ecological Interface Design for Hydropower System Monitoring and Control

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Abstract - *We describe a work domain analysis of a hydropower plant that operates in the two independent markets, the electricity market and the irrigation market. Based on the results of a work domain analysis, the authors develop configural displays that represent abstract functions of the hydropower system and that are intended as part of an ecological interface. The displays developed cover three critical segments of hydropower system operations: real time power supply operations, water storage management, and electricity trading. We provide detailed descriptions of the displays and of the expected improvements in control quality caused by the each of the displays.*

Keywords: Ecological interface design, work domain analysis, hydropower system, electricity market.

1 Introduction

Modern society has come to depend on reliable electricity as an essential resource for nearly all aspects of life. Power systems are very complex yet robust engineering designs that operate reliably most of the time. Much of power system operation is automated. Automation controls a power system successfully around a stable working point and executes functions that humans cannot perform as accurately or reliably as machines. However, without the help of the human operator, automation cannot resolve successfully many of the transient regimes of a power system. With the rapid progress of technology, there is a concerted effort to use automated system to augment human abilities. However, a lesson learned from process automation is that automation changes human operator activity and imposes new coordination demands on the human operator. The type and level of automation should be chosen in such a manner that the human performance consequences are negligible [1].

The recent blackouts in North America and Europe raise many issues in the power industry [2]. Here we underline only those that are connected to the human factor: high levels of human involvement in power system operations, the importance of the data management and its interpretation, and the small problems that lead to major problems if not corrected at the time.

In this paper we describe the complexity of hydropower systems as components in deregulated power systems and we point to areas that are and are not under automated control. We then present a work domain analysis of a hydropower system, identifying where the human controller exercises discretion in control. Finally, we present display concepts that reveal higher-order properties of the hydropower system to the controller and that reveal possibilities for action in the face of disturbances.

2 Complexity of hydropower systems

Hydropower systems consist of hydropower plants, storages, tunnels, and diversions. We outline some challenges encountered when attempting to automate some segments of hydropower system operations. Much electrical generation is now conducted within deregulated electricity markets. The transformation of the power industry changes the traditional monopolistic or regulated environment of a generating company into a competitive environment in the electricity market. Deregulation in the electric power industry has led to the integration of market operations with physical operations. The human controller becomes responsible for real time power supply operations; irrigation, and electricity trading.

For many companies the above developments have produced an accretion of information systems in the control room over a relatively short time. The continuing rapid development of the market has not provided much opportunity for the systematic design of automation. Key issues have been what to automate and up to what level of automation. Following Parasuraman, Sheridan, & Wickens, [1], automation can be applied to four classes of functions: 1. information acquisition; 2. information analysis; 3. decision and action selection; and 4. action implementation. The level of automation can be shown on a 10-point scale. At the highest level the computer decides everything and acts autonomously, ignoring the human. At the lowest level the computer offers no assistance and the human must make all decisions and take all actions [1]. As an introduction we will give a short description of existing forms of control, and levels and types of automation in hydropower systems.

2.1 Levels of automation and control

Power supply operation and irrigation are highly automated. The control of frequency (Hz), active power (MW), and reactive power (MVAr) are fully automated. In markets where a frequency control service is bid in, how much a generator provides frequency control is competitively determined in terms of MWs to be delivered within a specified time period for defined contingencies and for regulation. The human operator is responsible simply for starting generating units and arming the control systems accordingly. Thereafter, the operation of generators is fully automated; the automation executes all actions and then informs the human operator. During normal conditions the human operator monitors changes in system parameters. The response of automation (protection system) during a failure (deviation of a plant parameter from its nominal value) depends on failure severity. If the failure means that further work will endanger the safety of crew or equipment, or will cause further damage to the plant, the automation stops the plant, ignoring the human operator. The stopping procedure initiated by the protection system includes all steps necessary to take the plant to a stable and secure operating point. The automation will inform the human operator about non-critical deviations of the plant parameters; if the plant is in such condition the human operator must make a decision and take action.

There are several levels in the active power and frequency control hierarchy. The highest level defines the character of the active power and frequency control of whole hydro power system. There are three modes of control at this level that the human controller can choose from: (1) constant power, (2) constant frequency, and (3) constant power with frequency bias. Automatic generation control then executes the selected control mode.

The next level of of the control hierarchy controls how generation will be divided among the hydro power plants inside an aggregate unit (collection of power plants). The integration of two adjacent hydro power plants into an aggregate unit is common industry practice. The integration usually simplifies the control of the system but also gives more flexibility on the electricity market. There are three control modes here: (1) pond level control mode, (2) best efficiency mode and (3) control around a target allocated manually by the human to the hydropower plant.

How the desired generation is calculated for each generating unit is controlled at lowest level of the active power and frequency control hierarchy. There are several control modes at this level that differ in how the generator participates in minimising the area control error and how the base point of the generator changes during that process. The generation allocated to each generating unit is based on four criteria, (1) unit control mode, (2) base point value, (3) regulation factor, and (4) economic participation factor. Control is driven by a complex optimisation process. Usually the calculation of one solution requires several minutes. The human controller decides which control mode will be used, but control itself is fully automated. The various control loops all have manual control mode as a selectable option, but these days manual control is seldom used.

The control of reactive power and voltage is simpler than the control of a frequency and active power, and is based on the consumption or generation of reactive power according to the network requirement for decreasing or increasing voltage at a given point. The lower level of control is fully automated; this level of control is responsible for keeping a generator's bus voltage at a nominal value. The market for voltage and reactive power regulation ancillary services in the Australian electricity market is not automated. The market is based on long term contracts for supporting voltage in a particular area of the power system. Dispatch is based simply on a phone call, so control is fully manual. The human controller is responsible for changing the reactive power of synchronised units up to a level that will support the required voltage at the dedicated bus (usually neighbourhood transformer station).

Water management of a hydropower system is influenced by long/mid/short term planning for the irrigation and electricity markets. Water management is usually used for buffering hydraulic and power system constraints. Controllers are supported during decision making by software that provides information about different hydraulic dynamic processes (water surge calculations) and static processes (water flow calculations, lakes' water level calculation). The level of automation of subsequent steps in the chain of control can differ. Some control points are highly automated; the control system can keep water flow constant when that is desired. Other control points can be controlled remotely while the control itself is manual (change of a gate or valve position). Some control points require the involvement of a human who will manually open or close the valve/gate locally. The frequency of control operations around a control point principally influences the level of automation used.

2.2 Impact of the market

The introduction of the deregulated electricity market has changed how long, mid and short term scheduling of hydropower plants is done [3-7]. Traditionally, long-term hydrothermal coordination was formulated as a cost minimization problem, specifically to minimize the total system cost (usually, the thermal production cost). Mid-term and short-term cases used more detailed cost formulations. Hydropower systems were operated by controllers who made decisions with the help of computers. The goal was to secure a stable supply of electricity and to work within the system's physical and operational constraints.

The current kind of decision making process equivalent to long and mid term planning trades off between (1) present benefits, expressed as revenues from spot market, ancillary services market, and contracts, and (2) the potential revenue expressed as the marginal value of water stored in reservoirs [8]. The objectives of short term planning are to improve the efficiency of the generation system; to meet non-power requirements (irrigation); to manage transmission constraints; and to incorporate short-term marketing information and medium and long term marginal values of water into the decision making process of preparing generation and reservoir operation schedules [9-13]. Different optimization methods have been used in the past to help controllers make decisions. Today many hydropower generating companies use different optimisation software that fulfils the same task in a different environment (un-deregulated/ deregulated market) and with changed goals (cost minimisation/revenue maximisation).

3 Problem definition

Hydropower system operations can be divided into three areas of concern: (1) real time power supply operations, (2) water storage management, and (3) electricity trading. These three groups are strongly related. Existing automation does not provide adequate help to the controller for managing relationships between sub systems. In addition, current automation systems do not give an explicit answer to the question of what might be causing an operational constraint and what the possible future of the system might be in many situations.

The familiar four-stage model of human information processing has its equivalent in system functions that can be automated. Our intention is to augment human operator perception and understanding. The human operator requires support in perceiving and understanding three areas of hydro power system operations: real time power supply operations, water storage management, and electricity trading. We support each class of operations by a set of displays. In contrast, we leave to automation the information processing stage of information analysis for existing problems at the hydropower system. The main reason for not accepting different level of automation was trust in the automation system.

As a theoretical framework we used ecological interface design (EID). EID is starting to be widely used and has already passed different phases of validation [14-19]. The EID process consists of two stages. The first stage identifies the functional structure of a work domain. The second stage determines (1) content of the interface, (2) relationships between the content, and (3) form of the interface.

4 Work domain analysis

We used work domain analysis to analyse the functional structure of the work domain and so reveal the sources of its complexity. A detailed work domain analysis can identify what the content of the display should be to support controllers. The different levels of abstraction provide a view into the functional properties of the complex system in different conceptual languages, which can be different mental representations. The different levels of decomposition underscore the connection between the functional properties and the physical components of the complex system. The work domain analysis of the hydropower system is represented graphically in Figure 1 and is outlined in the following sections.

4.1 Functional Purpose (FP)

Objects at this level of abstraction correspond to the rationale behind the design of the system. The FP of the hydropower system can be described as an attempt to maximize revenue. Total Revenue consists of revenue made through the electricity market, and revenue made through the irrigation market if applicable. There are several components of the electricity market that have a large impact on the company’s financial gains: spot market, ancillary service market, hedge contracts, and settlement residues. Some of the components of the electricity market can generate losses: for example, the “causer pays” arrangements for financially penalizing market participants who create frequency deviations in the network, and hedge contracts. The goal is not to maximize or minimize any individual component of the gains and losses but to maximize the entire revenue of the company.

4.2 Abstract Function (AF)

Usually this level of abstraction describes the system in terms of first principles—that is, mass and energy conservation laws. In the case of a simple technical system the appropriateness of this is usually obvious [16, 17]. A complex system such as a hydropower system requires implementation of those laws in different time frames. The first equilibrium is the balance between available water mass and the released water mass through the generation of electricity and irrigation. This balance must exist in real time but also must be present in all bids and re-bids for processes in the future. The second equilibrium exists only in real time and is the equilibrium between the dispatched target and the delivered energy or services. Those simple explanations are however not fully adequate for understanding the complexity of a hydro power system.

The AF can also be viewed as a description of resources for achieving the functional purpose. Revenue can be maximized through the optimization of the long-, mid- , and short-term incomes as a function of present and future available water volume and present and future prices in the electricity market. The National Electricity Market Management Company (NEMMCO) is an independent system operator that administers and manages the Australian National Electricity Market (NEM), develops the market and continually improves its efficiency. NEMMCO is not a part of the hydro power system operations. NEMMCO is included in this work domain analysis because of the unique properties of electrical power systems compared with other domains involving human supervisory control. Electricity flows at close to the speed of light. Stability problems develop within less than 100 milliseconds. Energy cannot be stored, meaning that generation can only happen at the exact moment there is demand. Transients developed inside the power system are reflected in the electricity market almost instantaneously. These elements affect the future/present working point of the hydro power system and the financial gains and losses. The power system is sensitive to frequency and voltage changes and NEMMCO penalizes market participants who cause deviations. These characteristics of the power system are why some of the control of frequency and voltage are delegated to NEMMCO rather than handled by generating companies. NEMMCO has direct control over synchronised generators in order to regulate frequency.

The complex optimization of income and water availability has three elements: optimization of the bid/rebid, optimization of the merit order and development of the daily water plan. The hydro power company sells many products in the electricity market: (1) energy on the spot market, and (2) different kinds of ancillary services such as Voltage Regulation, Frequency Control Ancillary Service (FCAS), Network Control Ancillary Service (NCAS), and System Restart. The bid for each product consists of a MW quantity that the generating company wishes to generate at a price in a trading interval. Each participant in the electricity market can offer energy in up to ten price bands; and it is necessary to bid the price and the MW quantity at each price band. Settlement residues and hedge contracts are two financial instruments that can have a large impact on how a bid is constructed. Important components of the bid optimization structure are the existing/future constraints of the transmission network. Network constraints can be caused by voltage/frequency stability problems, faulty components elsewhere in the power system, ratings of transmission lines influenced by weather conditions such as temperature and wind speed or by ongoing maintenance of power system components.

The merit order prioritises the order and quantity of generation in each aggregate unit of the hydro power system. The important components of the merit order are water availability in the present and the future according to expected inflows and outflows. The next most important component are constraints that exist in the hydraulic network such as what the maximum change in a lake's water level should be over a day, the maximum change in water flow for any period of time, etc. The daily water plan is usually determined by the merit order and irrigation requirements. It should find a balance between the obligation to generate electricity and the availability of generating resources without violating constraints. The water daily plan should maximize the use of water for irrigation and generation at the same time if possible.

The Generation and Pumping control subsystem covers control of active power generation, the enabling and control of ancillary services, and control of pumping. Control should be optimized by taking into account the unavailable units (unit that are under maintenance), and unit constraints (maximum generation, minimum generation, rough running bands, ramp rate limit).

Components for control of water diversion are flow rate (ensures at the end of a predefined time period that the irrigation target has been reached), constraints (caused by construction and physical lows), and regulations (the flow rate ramp rate limit). Water releases (down spillways rather than through the power station) can endanger property and humans downstream. Regulations define procedures that will avoid such unwanted consequences. An auditory alarm is followed by substantial delay before releasing or increasing water flow rate. The delay should be sufficient for humans and movable property to be removed to a safe distance from the downstream flow.

Valves and gates differ in their level of automation. Units that can only be controlled locally and manually require employment of a field crew. To operate such components, additional communication is needed between the controller and field crew and additional time is needed to transport a crew to the destination, both of which further complicate control and following of the energy target. Valves and gates that can be remotely controlled are less demanding, and their control is simpler.

Whether from electricity market or irrigation contracts, revenue has several components: dispatched targets, deviations from targets, prices and penalties for unfulfilled obligations. The irrigation and electricity markets differ. The electricity market has an 'instantaneous' character; all dispatched targets should be followed instantly. The irrigation contract defines a volume of water that should be released during a contracted time period, rather than specifying a water flow rate. This allows deviations from the daily irrigation target as long as the overall target can still be reached at the end of the contracted period.

4.3 Generalized Function (GF)

It is not practical to decompose generalized function from the system level down through the subsystem level to the component level. All functions of the hydropower system (HPS) control centre, such as decision support, optimization, planning, and control, are common for the whole system. Decomposition is not possible without losing some functionality of that system. The general functions of NEMMCO such as pre-dispatch, dispatch targets, control, settlements, security, also cannot be decomposed further. The hydropower system can be decomposed into aggregate units and hydropower plants into generating units.

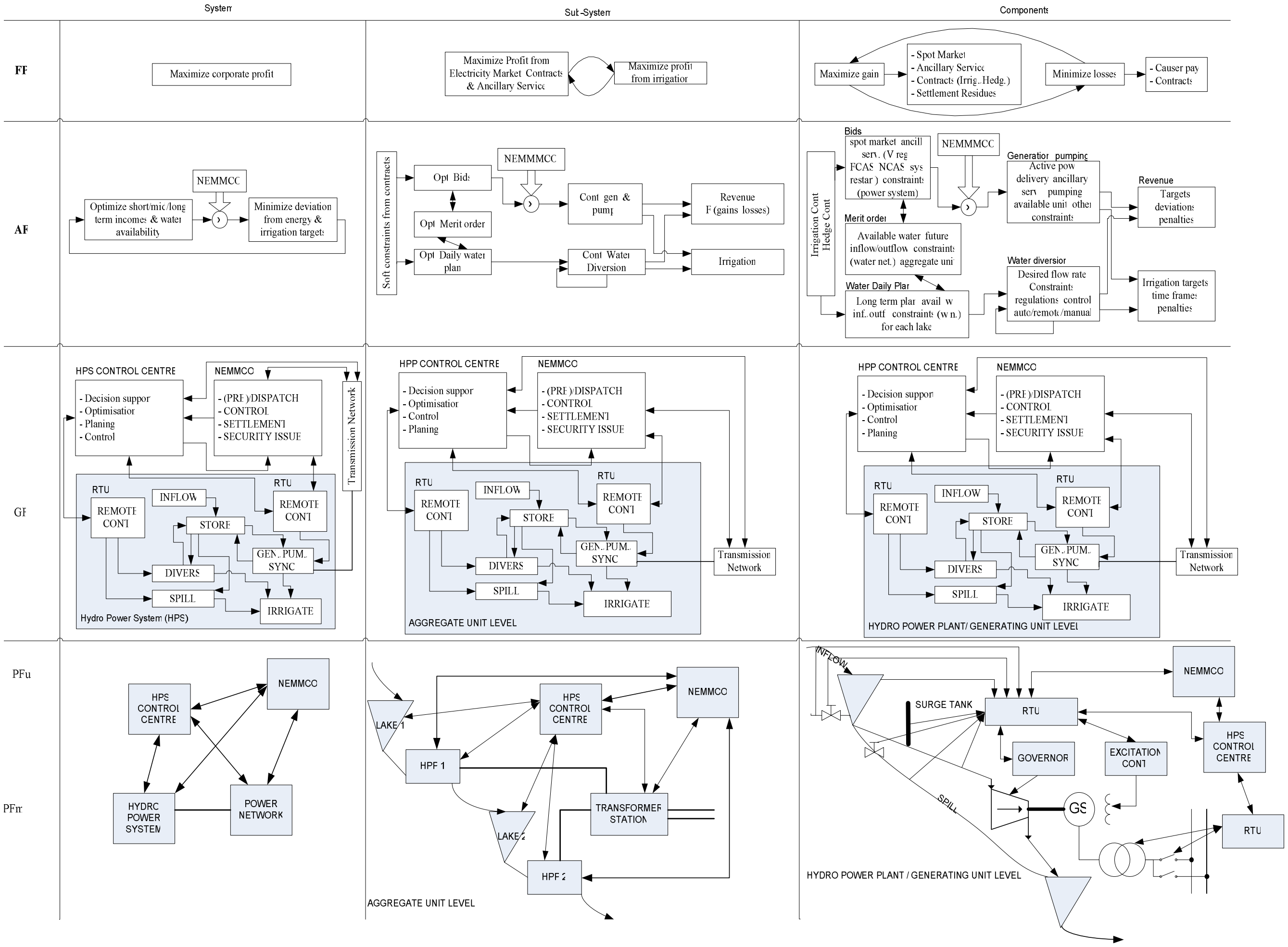

Figure 1. Work domain analysis of a Hydropower system

The GF of the HPS includes the following functions: store water, inflow, diversion, spill water, generate electricity, pump, generate reactive power (synchronous condenser), and remote control. The transmission network transfers electricity from the generators to the consumers. The transmission network is not part of the hydropower system, but the latter is often constrained by constraints in the transmission network. The instantaneous network configuration dictates how the HPS can be controlled (available transformer, buses, short circuit power). According to current practice, the generating companies have an overview of all important network parameters inside the neighbourhood transmission network.

4.4 Physical Function (PFu)

A detailed description of the Physical Functions of the components and sub-systems of the hydro power system is impractical given the space available. We will confine our description to components important for our work. To simplify our explanation we group components that have the same or similar function whenever possible. The major physical function of the lake is to accumulate water. Several components share physical functions; for example, the physical function of a tunnel and a penstock is to carry water from one place to another. The transmission line has a similar physical function but instead of water it carries electricity. Similarly it is possible to group valves, gates and spills according to function, which is to open or close in order to control water flow.

The physical function of a synchronous generator is to produce electricity. The physical function of the governor is to control the generator's active power and frequency. The excitation controller controls the voltage and reactive power generation. A fast change in a water flow rate caused by regulation of the generator will produce a water surge. The surge tank should suppress the water surge and minimize its impact on the turbine. The turbine's physical function is to use the pressure of water on a wheel to get mechanical power.

The circuit breaker's function is to stop an electric current automatically if it becomes too strong or dangerous. The physical function of a transformer is to change the voltage of a flow of electricity. The remote terminal unit (RTU) has several physical functions: control the belonging system, measure system variables, receive commands from the master system and send measured data to the master system.

It is not possible to decompose the physical functions of a HPS control centre and NEMMCO beyond the level of sub-system and system. On the engineering side, the physical function of the hydro power plant is to produce electricity. The entire hydro power system has the same physical function as a component system at the same level of the abstraction hierarchy. We should not be confused by the role of the synchronous condenser, or the pumping mode of some sychnronous generators. The synchronous condenser mode is a specific working mode of a generator unit in which generator generates reactive power and consumes active power. The pumping mode reverses the synchronous generator into a synchronous motor and the turbine into pump. Reversing of the generator will cause consumption of electricity and transforms the mechanical energy of the rotation inside the pump into kinetic energy and at last into the potential energy of water.

Components such as: transformers, circuit breakers, transmission lines are aggregated into the transformer station on the level of the sub-systems, and into the power network. The transformer station has the same physical function as a transformer. The physical function of the transmission network is to carry electricity from the generators to the consumers.

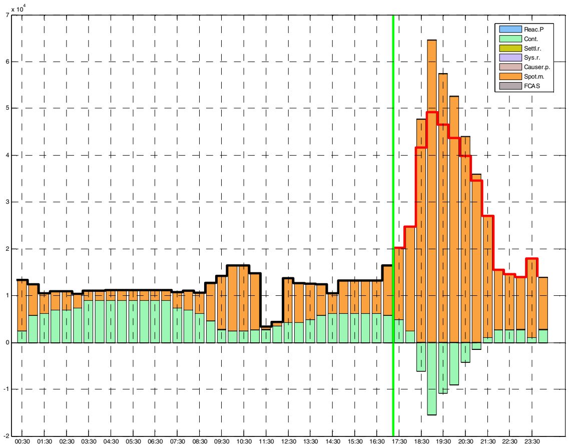

Figure 2. Revenue display

5 Ecological Interface Design

A display developed with EID principles should support three levels of cognitive control: skill-based behaviour, rule-based behaviour and knowledge-based behaviour. The idea of EID is to take advantage of operators' perception and action capabilities and to provide support for problem solving activities [14, 19]. The analysis of the hydropower system work domain underscores the need for strategic control. Strategic control provides to the controller a wider time horizon and control is less influenced by what has just happened. Strategic control provides the best control characteristics and ensures the achievement of high level objectives in a feedforward manner [20].

To support the controller in strategic control we developed three groups of displays: Revenue, Water Level and Efficiency, and Complex power display. To deal with present and future challenges in control the controller also needs information about past data and about soft and hard constraints [14]. Here we underline the need for a more efficient presentation of future states and more efficient presentation of the relationship between different levels of abstraction. All three displays emerge from the abstract function level of the work domain analysis in Figure 1.

5.1 Revenue display

The revenue display represents the gains and losses during one trading day (see Figure 2). A vertical green line indicates the current dispatch interval and divides past from future dispatch intervals. On the left of the vertical green line is a bold black line that follows revenue. On the right a bold red line presents forecasted revenue. The calculations of forecast gains and loses are based on the pre-dispatch values. This display supports the controller working with the company's trader in an attempt to secure high profit. One can recognize immediately the impact of the change in the availability of the hydropower system as a change in the "causer pays" component of revenue. Changes in the electricity market are also obvious through the change of the pre-dispatch target which will be obvious as a change in projected income.

5.2 Water level and efficiency display

The Water level and Efficiency display is shown for one lake in Figure 3. Multiple such displays will appear in an integrated format for all lakes across the scheme. The variables displayed on the display are: water level, efficiency of the water consumption, water inflow, and water outflow caused by generation of electricity, water outflow caused by spilling water, and the targeted lake's water level at the end of trading day. The same approach has been used on this display to separate the present and past from the future by a vertical green line. The elements of the graph have been arranged to improve the controller's perception of the critical variable, water level. The change in water level during the trading interval consists of several components: a light blue vertical bar that presents water inflow, a dark blue bar that presents a spill, and a violet bar that represents water outflow caused by generation of the electricity. Both the outflow spills plus water used during generation are organised into one vertical bar. The water level line connects the starting point of the inflow bar and the last point of the bar represents the use of water by generation. Calculations of future values are based on forecast values of local inflow, and calculations of water consumption and efficiency are based on pre dispatch values in the electricity market. The target water level is shown by the dotted green horizontal line. The calculation of the target level is based on the daily water plan and daily water target as a part of the irrigation target. The minimum operation level (MOL) (bottom red line) and full supply level (FSL) (top red line), are two hard constraints.

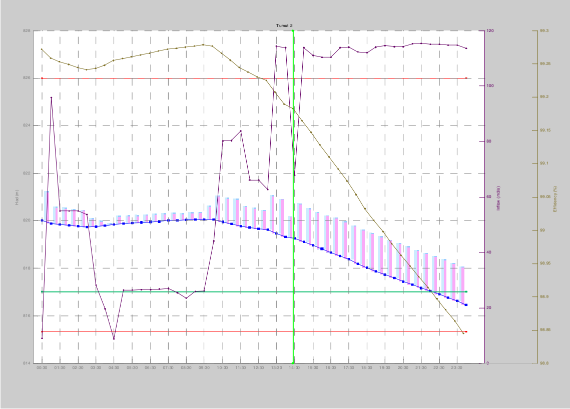

Figure 3. Water level and Efficiency display (one unit)

5.3 Complex power display

It is not possible to plan control of aggregate units or generators in fine detail a long way into the future. Unplanned outages inside the hydropower system or in the wider power grid can affect this level of control.

The Complex Power display (see Figure 4) should minimise the probability of control moving to the opportunistic mode or even worse to the scrambled control mode [20]. It shows current operating points, boundaries of safe operation, immediate past operating points, and possible future operating points. It also shows a network constraint (red circle), and aggregate unit constraint (unavailable capacity). The future working point is presented by the 4" and 5 min target and the past working point by the past 5 min target. The three physical modes of the generator unit are separated regions of the power circle: generator mode is in the right half, synchronous condenser is in the inner left half (yellow), and pump mode is in the left half. The raise and lower reserve of the generator capacity are obvious. The water level and pond mode control annotations should minimise the need to use other displays during critical control operations. As for the Water level and Efficiency display, there will be multiple Complex Power displays presented in an integrated format for all aggregate units in the hydropower scheme.

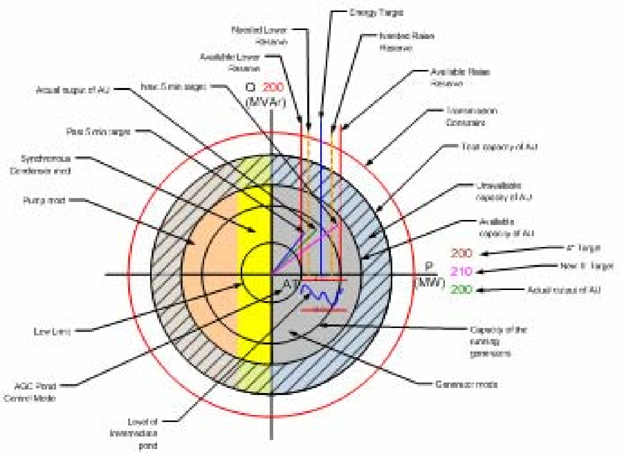

Figure 4. Complex power display

6 Conclusions

The display prototypes reflect qualities of EID as a set of principles for the display development. Our analysis of areas where automation controls a hydropower system helps to identify areas where the human controller has control discretion in the face of system disturbances, and so should be supported. The displays also demonstrate how the EID principle can be achieved of making visible the constraints of a work domain. The displays show how current system performance and future system states interact with constraints. This may less useful for fixed constraints than for dynamic constraints based on the interaction between several different fluctuating parameters. By being able to perceive where the performance of the system is and will be in relation to dynamic constraints, the operator can assess his performance and reason about possible actions. By making the boundaries of dynamic constraints explicit, an organisation can judge the most appropriate operating position, given its priorities and values.

The work domain analysis is not only useful for the development of the prototype displays but also for the analysis of the experimental scenarios. In other work we have developed measures of controller adaptation to system characteristics that might support better performance in the fact of contingencies. Tests of these and further displays [21] will confirm or challenge the proposed strengths of the prototype as outlined in the paper.

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