DESIGN OF ADVANCED GRAPHICAL DISPLAYS FOR THE TURBINE-GENERATOR SYSTEMS OF THE FORSMARK 3 SIMULATOR

Jordanna Kwok, Catherine M. Burns
Advanced Interface Design Lab, Systems Design Engineering
University of Waterloo, Waterloo, Ontario

ABSTRACT

As new technologies are introduced into the nuclear industry, there is increasing interest in replacing existing hardwired monitoring systems in nuclear power plant control rooms with innovative human-machine interface (HMI) graphical displays. However, investigations into past accidents at nuclear generating facilities have identified human performance limitations arising from HMI design as one of the most important factors in plant safety. Ecological Interface Design (EID) is a design methodology for HMI graphical displays that attempts to support operator performance for both anticipated and unanticipated events, which are often precursors to serious accidents.

The University of Waterloo and the University of Toronto are collaborating with the Norwegian Institute for Energy Technology (IFE) to examine the application of EID in the Swedish Forsmark 3 boiling water reactor nuclear power plant. This paper focuses on the design of advanced graphical displays for the turbine-generator systems.

Keywords: human-machine interface, graphical display, design, turbine, generator

INTRODUCTION

Recent field studies of operator monitoring strategies in nuclear power plant control rooms have revealed that performance is limited by the need to identify relevant information against a noisy background [1]. Much of the information related to the plant process is presented to the operators via a human-machine interface (HMI). In many existing nuclear power plants, operators rely primarily on HMIs that consist of hardwired indicators and alarms to determine the state of the plant. Secondary sources of information include status logs, maintenance records, and field personnel. Given the large amount of information that needs to be processed by the operators, human information processing limitations become apparent: attention, perception, problem solving, and decision making are some of the abilities affected. It is widely acknowledged that such abilities can be enhanced or restricted by the design of the HMI with which the operators interact.

Errors resulting from design deficiencies in the HMI at the Three Mile Island nuclear facility contributed significantly to the accident [2]. It was found that a major pressure relief valve indicator failed to reflect the actual position of the valve. As well, no indicator existed to show the exact water level in the reactor core. Various design guidelines have been established as a result of the Three Mile Island incident. With the introduction of modern display technologies (e.g. LCD monitors, large-screen projectors) in existing nuclear power plant control rooms, there is growing interest in the design of HMI graphical displays. It is hoped that the graphical displays will be able to convey relevant information needed by operators in a more efficient and reliable manner than previously with hardwired monitoring systems. In addition to design guidelines, a number of design methodologies for HMIs have been developed over the decade in order to overcome a variety of known human performance limitations and improve safety. Ecological Interface Design (EID) is one such design methodology that aims to support operator information processing in safety critical situations.

The OECD Halden Reactor Project hosted by the Norwegian Institute for Energy Technology (IFE) seeks to design and evaluate innovative HMI graphical displays for next-generation nuclear power plant controls rooms. The University of Waterloo and the University of Toronto are collaborating with IFE to determine the practical benefits of EID in the evolving nuclear industry. To date, we have designed and implemented EID graphical displays for the secondary systems (i.e. turbine-generator, condenser, and feedwater systems) in the Swedish Forsmark 3 boiling water reactor nuclear power plant simulator. The displays are currently undergoing a high-fidelity evaluation involving licensed nuclear power plant operators. This paper will discuss the design of the EID graphical displays for the turbine-generator systems.

ECOLOGICAL INTERFACE DESIGN

Ecological Interface Design (EID) is a relatively new interface design approach for complex socio-technical systems [3]. It has been applied to a variety of domains including process control, military, and medicine. EID differs from other design methodologies (e.g. User-Centered Design, task analysis) in that the constraints and complex relationships of the work environment are made perceptually evident to the users against a noisy background. By easing the acquisition of information, more cognitive resources such as attention can be allocated to more important processes in safety critical situations like problem solving and decision making.

Current empirical evidence suggests that EID is an effective approach for designing HMI graphical displays that support both anticipated and unanticipated events (i.e. untrained situations) [4]. Although EID graphical displays have previously been successfully implemented in simulator [5] and commercial [6] settings, most EID implementations have not been evaluated in representative industrial settings with trained operators [7]. The current study hopes to evaluate EID graphical displays for secondary systems with a state-of-the art simulated control room environment (HAMMLAB) and licensed Forsmark 3 operators.

The EID design process consists of two key stages: the Work Domain Analysis (WDA) and the Skills, Rules, and Knowledge (SRK) framework. In the WDA, models are developed to illustrate the physical and functional aspects of the system. Information relating to the system constraints and complex relationships are subsequently extracted from the WDA models. The extracted information is converted or mapped (i.e. designed) into graphical forms such that the constraints and complex relationships are visually salient to the operators. Much of the design is accomplished following the SRK framework, which describes the different kinds of behaviour or psychological processes present in operator information processing. For example, skill-based behaviour can be supported by designing a graphic that shows the difference between two values (see Figure 4) rather than requiring the operator to perform the calculation. The visual pattern is easy to see and requires minimal cognitive resources. Many advanced visualisation techniques have been established to achieve the jump from analysis to design [8].

WORK DOMAIN ANALYSIS

System Boundary

Given the complexity of the nuclear power plant in question, it was first necessary to define the physical boundaries of the secondary systems: turbine-generator, condenser, and feedwater systems. Recall that the scope of the study is limited to the secondary, non-reactor, side of the plant. The turbine-generator system consists of a number of physical components: one high-pressure turbine, three low-pressure turbines, a moisture separator reheater, a generator, and various control valves (see Figure 1). Because the operators are largely concerned with monitoring and controlling the plant process, specific components and subsystems were excluded from the boundary: control systems (e.g. governor), actuators (e.g. electro-hydraulic valve actuators), and sensors (e.g. pressure). Troubleshooting of the excluded components is typically carried out by maintenance and field personnel. Once the above items were established, the physical and functional attributes of the system were modelled following two WDA processes: part-whole decomposition and abstraction hierarchy, respectively.

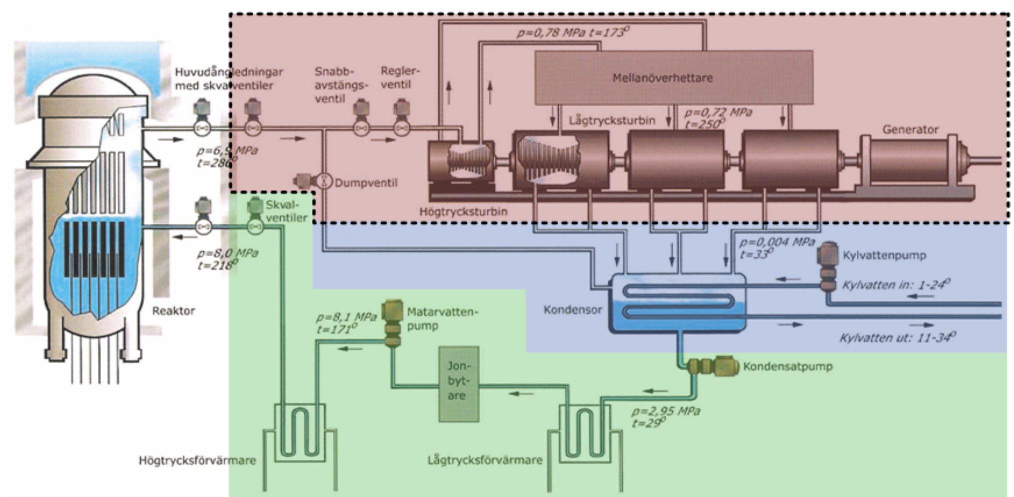

Figure 1: Turbine-Generator, Condenser, and Feedwater System Boundaries

Part-Whole Decomposition

A part-whole decomposition analysis yields a hierarchical model of the system at three different levels of detail: (1) system, (2) subsystem, and (3) component [8]. The model allows designers to determine how information can be grouped in the graphical displays. For example, high-level information found at the system level of detail (e.g. electrical output) is typically shown on overview or status displays. On the other hand, lower-level information found at the component level of detail (e.g. valve position) should be shown on detailed displays. The model also provides designers with a better understanding of the system from a physical stand-point. A variety of resources were used at this stage of the analysis including plant specifications, piping and instrumentation diagrams (P&ID), existing mimic displays, and process experts.

The turbine-generator system is represented by a black box at the highest-level of the part-whole model. Process materials flowing into and out of the system are illustrated. Essentially, the reactor transfers steam into the turbine-generator system for electrical power generation. Electricity is transferred out of the black box to various switchyards for consumer distribution. Exhaust steam and drain water also flow out of the turbine-generator system to other secondary systems including the condenser and feedwater systems. After identifying the system inputs and outputs, the black box was opened up to reveal numerous supporting subsystems: steam reheat system, seal and leakage steam system, lubrication and jacking oil system, seal oil system, and generator cooling system. The flow of process materials is again emphasised at the subsystem detail level. For instance, exhaust steam from the high-pressure turbine enters the steam reheat system before reaching the low-pressure turbines as superheated steam. The lowest level of detail was modelled by breaking down the subsystems into individual physical components; the resulting model is quite similar to a P&ID. The steam reheat system is comprised of a moisture separator, shell and tube heat exchangers, tanks and numerous valves (e.g. control, stop, check valves).

Abstraction Hierarchy

While a part-whole model provides details concerning the physical attributes of the system, an abstraction hierarchy (AH) focuses on the functional attributes. The AH analysis examines the means and ends (i.e. how and why, respectively) of the system by modelling it at five distinct levels of abstraction: (1) Functional Purpose, (2) Abstract Function, (3) Generalised Function, (4) Physical Function, and (5) Physical Form [3]. Elements at lower levels of abstraction provide the means to which elements at higher levels are achieved. The model is used at the design phase to determine what information to display along with the associated constraints and relationships. In addition, the information is organised based on the different levels of abstraction to promote knowledge-based behaviour as described in the SRK framework. The AH is one of the key defining characteristics of the EID methodology in contrast to other design approaches. Resources used at this stage of analysis include operator training manuals, textbooks, prior research, and process experts.

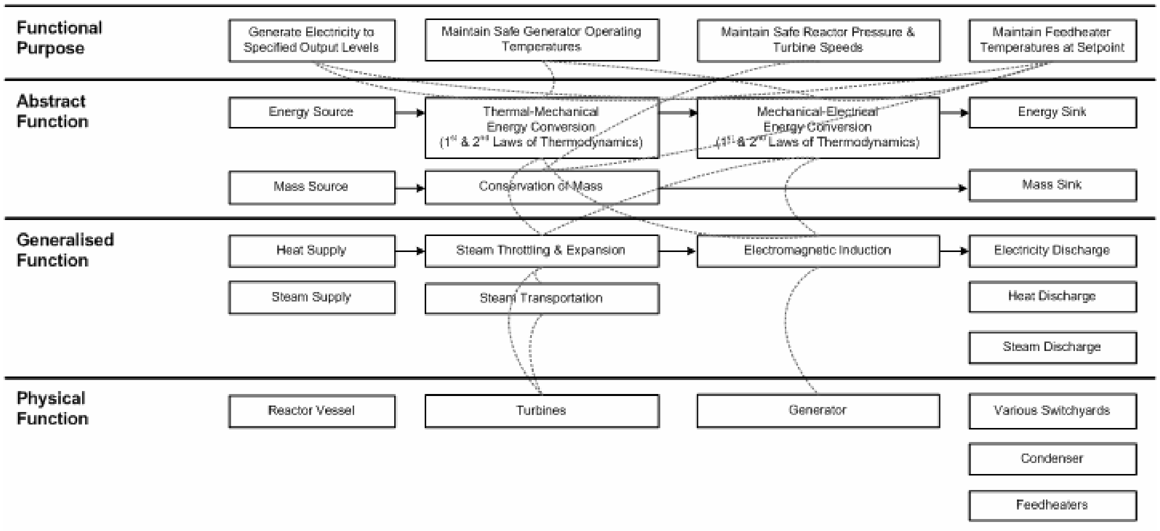

Figure 2: Abstraction Hierarchy at Part-Whole System Level [9]

The system was examined at each of the part-whole levels of detail yielding three separate AH models. At the part-whole system level of detail, the AH provides an overview of the black box (see Figure 2). Elements at the Function Purpose level describe the goals and purposes of the turbine-generator system. In a complex system, there are typically multiple goals that constrain one another due to practical limitations and tradeoffs. In the turbine-generator system, the goal of generating electricity is constrained by other safety targets such as maintaining safe reactor pressure. At the Abstract Function level, the laws and principles governing the goals are described. In this case, the first and second laws of thermodynamics along with the Faraday-Lenz law underlie the goal of electricity generation. Processes located at the Generalised Function level describe how the aforementioned goals and principles are achieved. The process of steam throttling and expansion is associated with the first and second laws of thermodynamics. Likewise, the process of electromagnetic induction is associated with the Faraday-Lenz law. Physical components or equipment related to the above processes, as previously identified in the part-whole decomposition analysis (e.g. turbines, generator), are shown at the Physical Function level. The physical properties for each piece of equipment (e.g. size, location, capacity) are then specified at the Physical Form level; note that this level was omitted from the current model for practical purposes.

Similar models were constructed from the subsystem and component part-whole levels. As expected, the results of the AH analyses at these two levels were of greater complexity, spanning several pages. One of the major challenges encountered due to the modularisation of the secondary systems was consistency between each subsystem. In effect, specific outputs of the turbine-generator system should be consistent with the inputs to the condenser or feedwater systems. For example, the energy sink representing steam discharge in the turbine-generator system should be shown as an energy source in the condenser system. The interactions between the systems were emphasised to avoid "losing" information during the design phase of the project. The AH models at the system part-whole level for the turbine-generator, condenser, and feedwater systems were in the end combined to aid the design of a large-screen overview graphical display.

GRAPHICAL DISPLAY DESIGN

Information Analysis

The information analysis stage attempts to bridge the gap between analysis (i.e. models) and design (i.e. graphical displays). Unlike other design approaches, EID relies primarily on the AH models to determine what information needs to be included in the displays. The information is based solely on the known capabilities of the system rather than on user experience or specific operating tasks. In a large system such as a nuclear power plant, it is often not possible to ask operators what they would like to see on the HMIs. The suggestions tend to vary widely based on expertise, while some operators feel that there is no need to include more information. Furthermore, information based on task analyses does not necessarily support unanticipated events; tasks are known anticipated events. The EID methodology concentrates on obtaining information that supports both anticipated and unanticipated events. However, it is possible to combine multiple design approaches to provide complementary information in the HMIs [8].

Information to be translated on to the EID graphical displays is obtained by extracting variables from the AH models developed in the previous phase [8]. The variables are identified by asking how each element in the AH can be measured. For instance, the goal of generating electricity to a specified set point can be measured by real and reactive power output variables. Measures related to flow, balance, and conservation were extracted from elements at the Abstract Function level. Likewise, process related variables such as temperature and pressure were identified at the Generalised Function level. At the Physical Function level, equipment can be measured, in a sense, by looking at its capacity and capability.

Each extracted variable contains additional information regarding its availability, constraints, and relationships with other variables. These attributes serve as design parameters for creating graphical elements and were recorded in tables for easy referencing (see Table 1 for an example entry). Variables can be measured via sensors, calculated from other variables, or are simply not available in which case cannot be designed into the displays. Like many existing power plants, energy cannot be measured through sensors. Instead, the value must be obtained through a steam table lookup using temperature or pressure values. Two types of constraints exist for variables: single variable constraints and multivariate constraints. The range-limit of a particular variable (i.e. maximum and minimum values) is considered a single variable constraint. The relationships between multiple variables are considered multivariate constraints. Energy leaving the reactor is related to energy into the high-pressure turbine in that the two are approximately equal (see Table 1). It is possible for one variable to be related to another through complex mathematical expressions as dictated by known physical models. Apparent power, for example, is equal to the hypotenuse of a right-angle triangle consisting of real and reactive power (see Figure 6). The relationship is known as the power triangle. The following section describes how the extracted variables and related properties were transformed into graphical forms.

Table 1: Extracted Variable at the Abstract Function Level

Variable	Energy in from the reactor
Description	Specific enthalpy of steam leaving the reactor
Units	kJ/kg
Availability	Calculated: steam table lookup
Constraints	Max: ~2,772.1 kJ/kg Min: 0 kJ/kg Normal: ~2,742.1 kJ/kg
Relationships	Approximately equal to energy into high-pressure turbine

Graphical Forms and Organisation

As indicated above, the table of variables provided the designers with parameters for graphical visualisation. Specifically, the constraints and relationships of the variables were incorporated into the graphical forms and organised in a manner to conform to the SRK framework. In the turbine-generator displays, a number of advanced visualisation techniques such as emergent features were used to emphasise variable constraints and relationships. A single variable such as turbine vibration (see Figure 3) is limited by a maximum and minimum value. The two vertical bars in the middle are a visual indication of the maximum value; if the middle black vertical bar representing the current value deviates (i.e. rotates) too much, it will hit the two surrounding constraint bars. For multiple variables such as mass flow (see Figure 4), generator-grid parameters (see Figure 5), and power (see Figure 6), the relationship between the variables were made apparent. In the mass balance graphic, the balance between the two bars is accentuated by a horizontal bar containing a bubble. According to the conservation of mass, the two bars should be equal in height and the horizontal line should not be tilted. The bubble is analogous to a carpenter's level, rising when the line is tilted, and providing a visual indication of the mass flow rate of change. The variables involved in the synchronisation

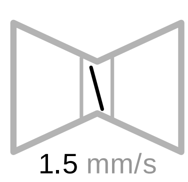

Figure 3: Single Variable at the Physical Function Level (Turbine Vibration)

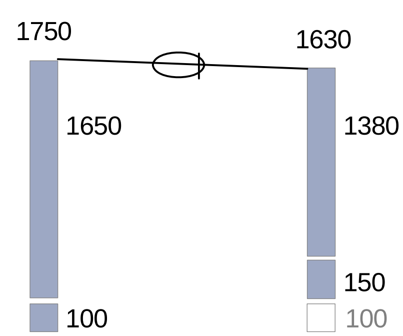

Figure 4: Multiple Variables at the Abstract Function Level (Mass Flow)

of the generator to the grid are traditionally shown in an indicator known as a synchroscope. The voltage, frequency, and phase differences are associated with different aspects of the synchroscope dial (e.g. spin direction, speed). Rather than requiring operators to memorise the relationship of each dial aspect, the parameters can be mapped graphically on a sinusoidal wave. The generator is synchronised with the grid when the black sinusoid (i.e. generator voltage) matches the grey sinusoid (i.e. grid voltage). The differences between the generator and grid parameters are also emphasised in the graphics found below the sinusoids.

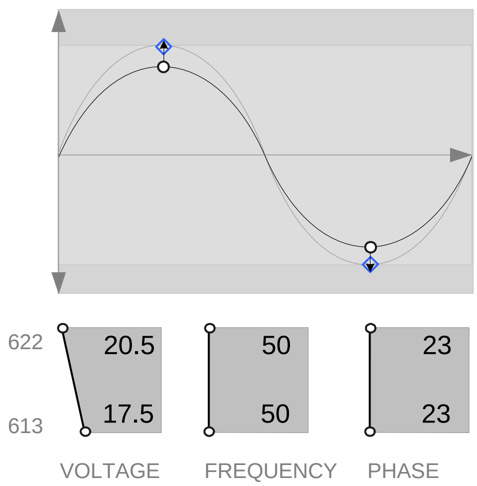

Figure 5: Multiple Variables at the Generalised Function Level (Synchrometer)

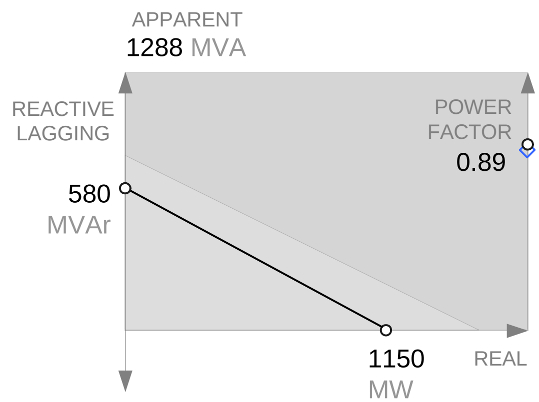

Figure 6: Multiple Variables at the Functional Purpose Level (Power)

The graphical elements representing single and multiple variables are intended to promote skill- and rule-based behaviour described in the SRK framework. In order to support knowledge-based behaviour, as discussed earlier, the graphical elements can be arranged according to the AH [4]. The graphical elements representing variables at the Functional Purpose level were organised mainly along the top of the displays (see Figure 7, 8). The balance, flow, and process variables were grouped together by abstraction level and distributed throughout the rest of the display. The associated equipment and physical properties were placed between the higher-level information in a mimic fashion. The salience of the mimic graphics in the turbine subsystem display was reduced to reflect the level of the information due to large amount of information. The embedded structure of the AH allows operators to create an appropriate mental model of the information being processed.

CONCLUSIONS AND FUTURE WORK

Unlike other design approaches, the EID methodology follows a well-formulated engineering process involving both analysis and modelling. Often times, the analysis provides more information than desired by the operators. It was argued that since mass flow information is not traditionally available in control rooms, operators would overlook or ignore the information. However, it is this type of information that provides operators with a visual indication of the plant process limitations. A fault occurs when one or more of the limitations (i.e. constraints) are violated. Accordingly, operators are expected to more readily detect faults in EID graphical displays for both anticipated and unanticipated events [4]. Given that the deviations from normal operating conditions can be easily perceived, more cognitive resources are available to the operators for determining the underlying cause. The problem solving process is particularly important in unfamiliar events as there are no procedures to follow. An empirical evaluation of the EID graphical displays is currently under way to determine whether the aforementioned benefits are applicable in representative industrial settings.

The study will compare the existing mimic displays on the Forsmark 3 simulator to the EID graphical displays discussed in this paper. The existing mimic displays were designed primarily through a user-centered approach, which relied on the expertise of the consulted operators. Trained and licensed operators from the Forsmark 3 nuclear power plant have volunteered to test the displays on a high-fidelity simulator (HAMMLAB). Operators will be using the displays to monitor and control the system under various anticipated and unanticipated events. Quantitative measures will include operator performance (e.g. response times) and situation awareness. Interviews will also be conducted to obtain usability and acceptance data. We expect the results of the study to provide practical feedback on the viability of the EID methodology in next-generation nuclear power plant control rooms.

ACKNOWLEDGEMENTS

This project is supported by the NSERC Special Research Opportunities program. We would like to thank Christer Nihlwing (Process Expert at IFE), Gyrd Skraaning Jr. (Experiment Lead at IFE), and the Halden implementation team for their expertise. Special thanks to Jon Kvalem for making this collaboration possible.

REFERENCES

[1] R. J. Mumaw, E. M. Roth, K. J. Vicente, and C. M. Burns, “There is more to monitoring a nuclear power plant than meets the eye," Human Factors, vol. 42, pp. 36-55, 2000.
[2] J. G. Kemeny, Report of the President’s Commission on the Accident at Three Mile Island. U.S. Government Printing Office, Washington, D.C., 1979.
[3] K. J. Vicente and J. Rasmussen, “Ecological interface design: Theoretical foundations,” IEEE Transactions on Systems, Man, and Cybernetics, vol. 22, pp. 589-606, 1992.
[4] K. J. Vicente, “Ecological interface design: Supporting operator adaptation, continuous learning, distributed, collaborative work,” in Proceedings of the Human Centered Processes Conference, 1999, pp. 93-97.

[5] N. Dinadis and K. J. Vicente, "Ecological Interface Design for a Power Plant Feedwater Ssytem," IEEE Transactions on Nuclear Science, vol. 43, pp. 266-277, 1996.
[6] J. Itoh, A. Sakuma, and K. Monta, "An Ecological Interface for Supervisory Control of BWR Nuclear Power Plants," Control Engineering Practice, vol. 3, pp. 231-239, 1995.
[7] G. A. Jamieson, "Empirical Evaluation of an Industrial Application of Ecological Interface Design," in Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society, 2002, pp. 536-540.
[8] C. M. Burns and J. R. Hajdukiewicz, Ecolgical Interface Design. Boca Raton, FL: CRC Press, 2004.
[9] J. Kwok and C. M. Burns "Ecological Interface Design for the Turbine Subsystems of a Boiling Water Reactor," in Proceedings of the 16th World Congress on Ergonomics, 2006, in press.

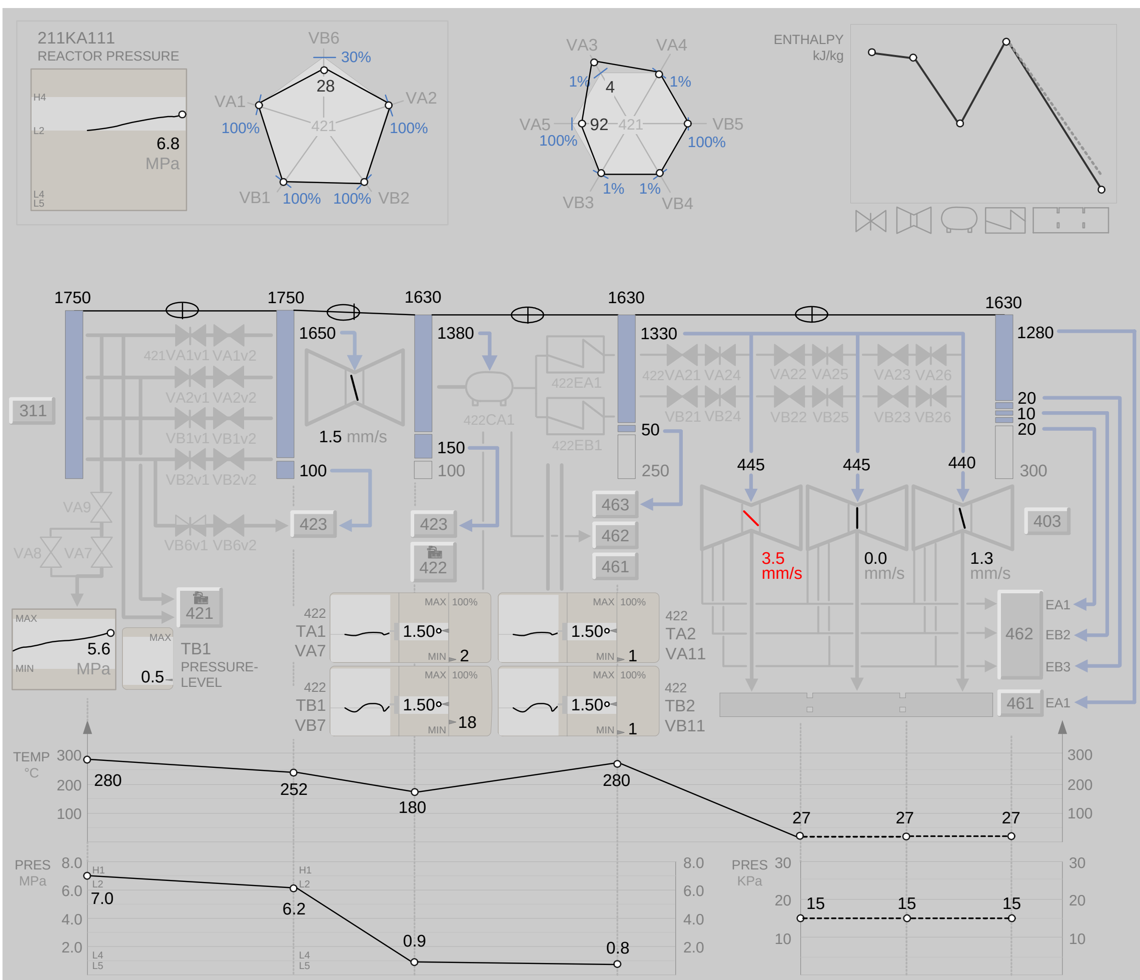

Figure 7: EID Graphical Display of the Turbine Subsystem

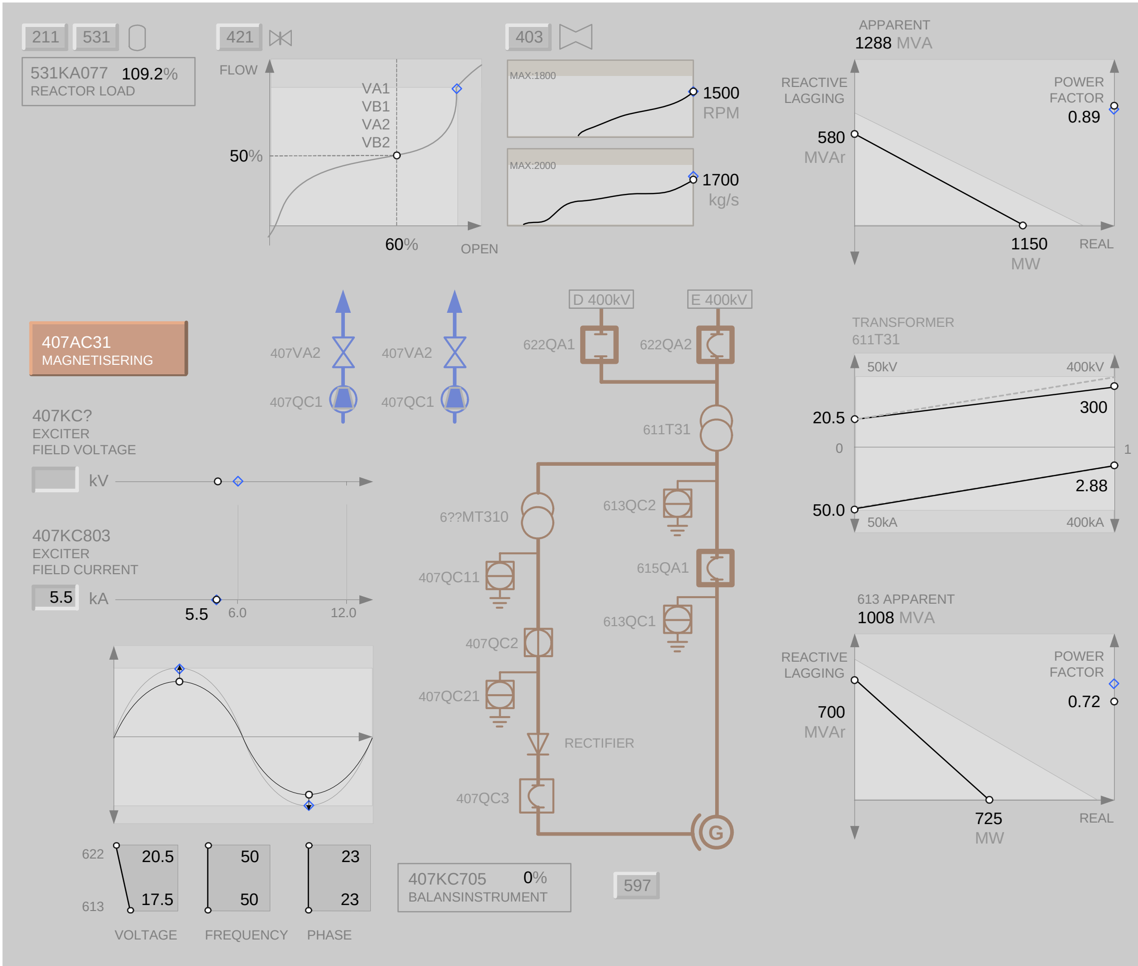

Figure 8: EID Graphical Display of the Generator Subsystem