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Operational Challenges To Feedwater / Steam Generator Water Level Control

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ABSTRACT

Feedwater control and turbine control have historically been at the top of the list of contributors to unplanned outages and forced curtailments in the nuclear industry, and they remain so according to recent industry data. Much has been done and is available by way of measures to improve this area and, in spite of much progress, opportunities remain to extend implementation. Toward this end, this paper aims to focus upon feedwater control and provide background on associated characteristics and attributes as a context for identifying the issues which are key challenges that lie at the root of this concern. Primary groupings of these issues will be discussed in order to better define their nature and to establish a basis for a presentation of the range of solutions which have been implemented and remain available to address them. The need for a systems engineering approach, and the role of I&C and field-mounted equipment to application of these solutions will be discussed.

1. FEEDWATER CONTROL: HISTORY OF CHALLENGES

Feedwater control and Turbine control have historically been at the top of the list of contributors to unplanned outages and forced curtailments in the US. There have been many contributing factors to this, however upon evaluation they fall into three fundamental categories: plant process related, field interface related, and I&C system related. The characteristics of factors associated with these three respective categories suggest a range of varying solutions, and much has been done to mitigate the impact of such challenges over the last roughly 25 yrs of operational experience. Industry assessments have been performed in order to identify the type and nature of these challenges so as to provide a basis for development of solutions to address them, and results have led to programs for their implementation. Such trip reduction programs also included extension into the realm of I&C upgrades and implementation of associated modifications. This paper aims to provide some of the background of this industry experience, as well as an overview of developments, particularly with regard to I&C upgrades, up to the present.

1.1 Early FW Industry Initiatives - US

In the mid 1980’s, the Nuclear Management and Resources Council (NUMARC) established a goal to reduce unnecessary reactor trips. Industry data accumulated from 1979 thru 1985 indicated that nearly 40% of reactor trips in plants of Westinghouse design (pressurized lightwater reactors, i.e. PWR's) were in some way related to feedwater control, alternatively referred to as steam generator water level control. In response to establishment of this goal, the Westinghouse Owner's Group (WOG) initiated a Trip Reduction and Assessment Program (TRAP) in order to identify a solution path toward operational improvements which could tangibly offset the frequency of feedwater related reactor trips and the corresponding impacts to plant availability and capacity factor. [1]

1.2 Early FW Results

The WOG-TRAP program initially focused on margin to trip, i.e. the operation margin between the normal operating point for the trip-related parameter, namely steam generator water level, and the measured limits which would result in reactor trip, e.g. low level (direct reactor trip) and high level (causing turbine trip with resulting reactor trip at moderate and high power levels). Several approaches were identified to mitigate adverse impacts to this margin. First of all, efforts were made to refine the analysis limits upon which the trip setpoints were based. Secondly, efforts were undertaken to reduce the instrumentation uncertainties necessary to be accounted for in establishment of measured limit setpoints in relation to the analysis limits. In this regard, several modifications were developed which provided the capability to enhance margin through reduction of instrument uncertainty, e.g. trip time delay, environmental allowance modifier, level-tap modifications, etc. [2]

With this initial set of features and considerations as a basis, WOG-TRAP expanded its focus to include solutions in the area of operation performance and control. Some such solutions related to enhanced operator support so that manual feedwater control operations could be undertaken with increased effectiveness and reduced risk of inadvertent trip. These came in the form of optimized/streamlined operational procedures, enhanced training, and augmentation of the human-system interface with proposed introduction of graphic displays incorporating functionally enhanced data presentation. While these options provided a degree of potential improvements beyond those afforded by margin improvements, their effectiveness was inherently limited as they continued to rely upon manual control operation by the operators. Such dependency also brought with it a range of variability depending upon the experience profile and capabilities across various crews of operators. In order to address these limitations, the next phase of attention in the WOG-TRAP program had to move directly toward consideration of modifications to the automatic control system itself.

2. ROOT CAUSES OF OPERATIONAL FEEDWATER CHALLENGES

Before discussing specific changes to the design of the automatic control system, it is important to consider the particular aspects of feedwater control which underlie operational challenges, whether they be in the context of an operator controlling in manual, or a system operating in automatic. The same set of factors and characteristics are at the root cause of these challenges and, as described earlier, fall broadly into the area of plant process, field interfaces (both measurement and control related), and the I&C platform itself. All of these, in their own way, contribute to the circumstances which resulted in many of the feedwater related trips occurring during manual control of feedwater, often with multiple operators being required to support low power operations and unit startup. This was the case particularly for plants having multiple reactor coolant system primary loops, and associated multiple steam generators. While the shortfalls of manual operator control under these sorts of conditions were evident, similar shortfalls existed in the form of control algorithms being applied in the automatic control system, thereby resulting in ineffective and sometimes unstable, and effectively unusable, automatic control performance.

2.1 Plant Process Characteristic

As the control system design problem begins fundamentally with the process being controlled, likewise discussion of these challenges begins with the nature of steam generator water level dynamic response behavior, and the associated interfacing plant processes which impact upon it. First and foremost in this regard is the non-linear, non-minimum phase response characteristic of steam generator water level changes resulting from changes in feedwater flow, also classically referred to as “shrink-swell”.

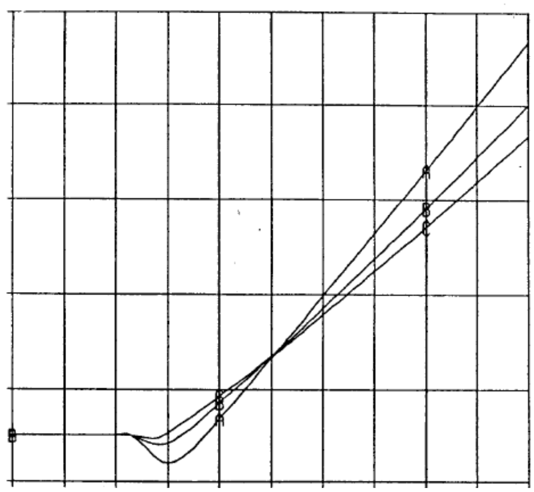

Figure 2-1 Representative Steam Generator Water Level "Shrink-Swell" Behavior

Under steady-state conditions, the introduction of an increase of feedwater flow would be expected to result in a corresponding increasing change in level which is, in fact, indicated in the above figure in the long term. There is, however, in the short term a drop or “shrink” in level which results from the introduction of relatively colder feedwater into the recirculating two-phase flow of water mass in the steam generator, thereby causing a slight net reduction in temperature with corresponding contraction of volume. Various effects can influence the degree of shrink reflected in the level measurement signal, however, in general terms the effect becomes larger as feedwater becomes colder, i.e. at lower power levels, particularly with the turbine offline and corresponding lack of feedwater heating. A similar opposing ‘swell’ effect results initially from a decrease in feedwater flow. This type of behavior is evidenced not only on vertical steam generators, but horizontal designs as well.

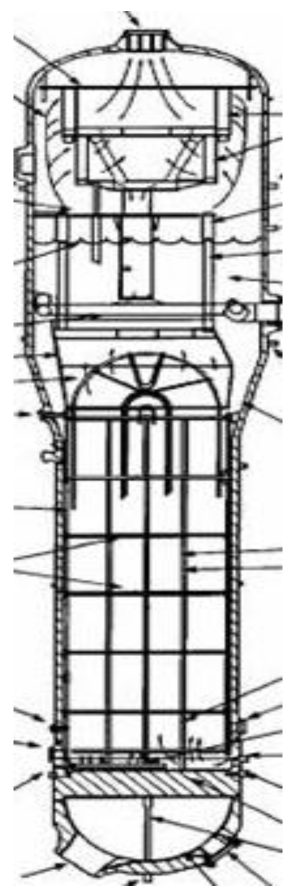

Figure 2-2 Typical Vertical U-Tube Recirculating Steam Generator

From a control standpoint, the adverse impact of such ‘non-minimum phase’ behavior can be illustrated by considering the example of steering control for an automobile. Imagine a car being driven down a long straight highway with a bend to the left approaching in the distance. In preparation for easing into the turn, the driver would normally begin to turn the wheel to the left in the expectation that the car would likewise begin to track leftward. However, if the car were subject to non-minimum response behavior, it would first veer slightly to the right in response to the left turn of the steering wheel before subsequently trending left. Naturally, this would present a confusing challenge to the driver of the car, and would certainly complicate design of an automatic steering system were such a design to be undertaken.

Additional challenges for steam generator water level control result from attributes of the mechanical feedwater system, for example variations in system piping configuration and/or variations/asymmetries between parallel feedwater paths feeding multiple steam generators. Such variations can yield differing response and/or operating points between loops.

Further challenges come as a result of the multiple control devices employed in the service of the feedwater plant process, i.e. feedwater pumps and regulating valves. Plants would most typically have at least two, and perhaps three main feedwater pumps, and they could be of similar or differing type, i.e. variable speed/turbine driven versus constant speed motor driven. These could be supplemented by startup pumps at low power or heatup/cooldown conditions and, in any case, are always supplemented by some form of auxiliary feedwater system design to support post-trip conditions and which are sometimes utilized to augment normal startup operations. The multiplicity of driving pumps and flowpaths for feeding results necessarily in operational transitions for bringing these pumps and corresponding flowpaths into and out of service. Such transitions are often performed manually by the operator. In addition to the pumps, there also typically exists a combination of smaller bypass feedwater regulation valves working in parallel with larger main feedwater regulation valves which together provide the capability for modulating feedwater flow with necessary accuracy and precision over the complete range of power operation. Operational transitions are likewise required between these sets of valves, and for traditional systems, these transitions entailed manual intervention by the operator. Every such manual demand placed upon the operator presents a challenge and potential for adverse control leading to reactor trip.

2.2 Field Interface Characteristics

In addition to the attributes of the steam generator and feedwater system, field interfaces such as control devices (pumps, valves) and measurement sensors and have their own operational properties and dynamic response characteristics. Valves are well known for their non-linear flow/lift characteristics, and pumps similarly have a non-linear head/flow characteristic. In addition, positioners working in conjunction with the mechanical valve response result in a particular dynamic time response characteristic, as do servos for certain pump arrangements. With the introduction of digital valve positioners and their attendant capabilities for customizing valve response characteristics, both proportionally and dynamically, another degree of variation can be introduced which can influence overall control system behavior. [3]

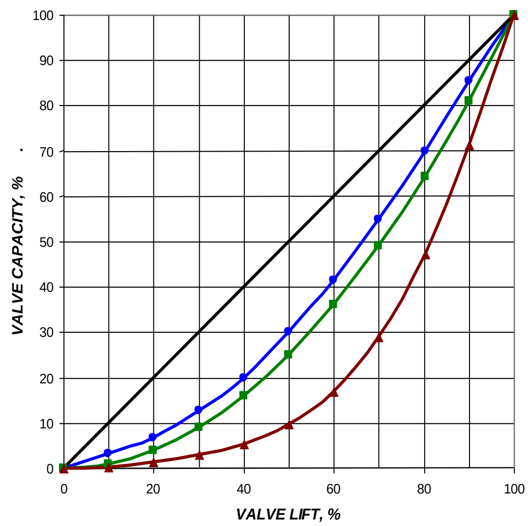

Figure 2-3 Representative Valve Flow/Lift Characteristics

With respect to input signals used for control and indication, it is recognized that delta-P measurement devices used in support of feedwater/steam flow do not provide a signal of suitable quality at low flow values (typically below 15-20% of range) due to the noise considerations compounded by the non-linear (square) relationship of flow to pressure drop. As a result, traditional three-element (level, steam flow, feedwater flow) based control logic can be employed effectively at higher power levels, but cannot be applied for low power levels. Thus, this limitation directly impacts the approach to control design for the steam generator level control algorithm. Furthermore, redundancy (or lack thereof) and time response considerations must also be addressed relative to these measurement devices in order to facilitate reliable and effective control.

2.3 I&C Characteristics

Having discussed the plant process and interfacing equipment, the remaining considerations relate to characteristics of the I&C equipment itself. By their very nature, legacy analog (and even some early digital) I&C platforms are limited in their capability to provide functionality which can address and offset challenges in other areas related to feedwater control, thereby introducing a challenge in and of themselves. For example, the inability to readily introduce adaptive or variable tuning into the control algorithm to account for process or field device non-linearities results in the need to implement fixed tuning parameters selected as a ‘best-reasonable fit’ for expected response characteristics over the entire range of power operation. Likewise, the ability to implement backup or alternative modes of operation which are context dependent typically results definition of system-level operational mode having two possible states. Finally, the operator interface is limited to traditional indicators, status, and recorders thereby limiting the view into the state of the process and associated interfaces in support of situational awareness, diagnosis, and action formation/implementation in the face of evolving operational demands or circumstances.

Another significant challenge posed by the I&C platform, particularly for legacy analog systems, is the existence of single points in the system capable of directly impacting operations in the event of a failure, so-called ‘single-point-vulnerabilities’ (SPVs). This is due to the limited redundancy and fault tolerance built in to legacy analog as well as some early digital I&C

platforms. Aging equipment presents ever increasing risk of availability impacts do to these considerations and serves as the primary motivation for many reliability-centered and predictive maintenance programs. Incremental benefit can be derived from these sorts of programs, however it must be recognized that while risk can be mitigated via change-out of aging components (e.g. RCM program), risk cannot be eliminated entirely due to the fundamental nature of the legacy I&C architectures which, particularly in the case of analog, are comprised of serial thread-path strings of modules/components, each of which represents an SPV.

3. I&C UPGRADES RELATED TO FEEDWATER CONTROL

3.1 Context of I&C Upgrades

With the above understanding of the factors which offer challenges relative to feedwater control, consideration can be given to the overall context for defining potential I&C upgrades to help in addressing them. Since the mid-80’s during which a particular focus upon improvement of feedwater control had begin, industry has moved toward support aging units with incremental I&C modifications in the face of increasing obsolescence, operational challenges, and personnel turnover. As such, efforts to incorporate upgrades have been largely done on an ad-hoc basis. However, the above root causes which challenge feedwater control cover a range of considerations which, taken as a whole, suggest the need for a more integrated approach, i.e. a systems engineering solution in order to address the following areas and realize attendant benefits in their regard:

a) Account for process characteristics

b) Acknowledge I&C characteristics & interfaces

c) Leverage Physical and Functional Design Attributes

d) Utilize a structured design & implementation process for upgrades & modifications

3.2 Goals of I&C Related Solutions

In view of the above, implementation of any I&C solution must address both I&C platform challenges, as well as operational challenges. Toward this end, the chosen replacement I&C platform must incorporate features which inherently mitigate the driver discussed, namely, equipment obsolescence, single point vulnerabilities (SPV’s), limitations of analog technology, and unreliable measurements. From an operational standpoint, the I&C upgrade must provide for enhanced performance in support of reduced unplanned outages/curtailments, system stability, dynamic responsiveness for anticipated normal operational transients, as well as reduced operator demands in general. The I&C solution should also provide prognostic capabilities so the end user can plan plant evolutions instead of reacting to unplanned system events or challenges.

3.3 Aspects of I&C Related Solutions

In alignment with the stated goals related to both platform and operational challenges, implementation of I&C solutions must incorporate both physical and functional features as necessary and applicable to not only address the challenges enumerated above, but to provide enhanced performance beyond the baseline established with legacy systems in past years of operation. With regard to the I&C platform, this would entail implementation of fault-tolerance at the level of electronics, I/O, power, as well as the human-system interface (HSI). With increasing frequency, upgrade project are also including smart/enhanced devices (sensors/positioners) and upgraded control device interfaces to expand the physical considerations beyond the limits of the I&C platform itself.

While reliability can certainly be address via the noted platform considerations, and a degree of enhanced operational performance might be obtained through upgraded field devices, enhancement of overall dynamic performance capability for operation during transients of even moderate significance will necessarily involve introduction of new and/or augmented features relative to system functionality. This most directly manifests itself in the form of enhanced control algorithm/logic and involves changes to signal compensation, controllers and associated tuning constants, alternate modes with auto transfer between modes (i.e. alternate-actions to allow continued automatic operation in a degraded state in response to selected failure conditions), and enhanced HSI (typically including soft -control). Provided sufficient signal redundancy exists, fault tolerance inherent to the platform architecture is typically further supplemented and reinforced as well through the introduction of automatic signal validation.

4. TIMELINE: FW CONTROL UPGRADES APPROACH

Industry experience in the US with respect to incorporation of I&C upgrades to address feedwater control challenges has evolved through roughly two periods of evolution which more or less align with three progressive generations of I&C system, so-called Generations I, II, and III. The first generation of I&C system refers to the initial installed system, typically analog though on occasion early digital. The functionality of these systems can be generally characterized as traditional 3-element control (level, steam flow, and feedwater flow), sometimes augmented with distinct high power and low power modes. The second generation of I&C systems introduced the first wave of digital upgrade projects and incorporated not only a new digital platform having all the inherent benefits of reliability/fault tolerance, but also typically incorporated an enhanced 3-element control approach having integrated high/low power modes with automatic and seamless transition of modes, not only within the system but also with regard to staging of selected components (e.g. bypass and main feedwater regulation valves).

This first wave covered the late ’80s and early ‘90s, eventually moving into the second wave which introduced the next generation of upgrade which built upon Generation II with incorporation of enhanced functional features within an updated digital platform.

To the extent that system performance requirements speak both steady-state stability (the main concern for a significantly large majority of the time during operation) as well as dynamic transient response (admittedly a small, but overridingly important percentage of operational), a traditional design trade-off results. Both aspects must necessarily be treated with equal importance, since a highly responsive system cannot introduce fluctuations or limit-cycle behavior during steady state operation; likewise, steady-state stability cannot be achieved to such a degree that dynamic transient performance is degraded. Both aspects can be impacted by a variety of factors related to characteristics of the plant process, interfaces, and control system design as discussed above, and efforts to deal with the noted trade-off must necessarily address the entire control closed-loop. As a result, this suggests that certain elements be present in the design and test process employed in support of any such upgrade in order to realize the fullness of potential benefits.

4.1 Design & Test Process Attributes

In this general regard, it is fundamental that all control system upgrades undergo a structured process, including hierarchical levels of testing in order to introduce assure these necessary elements. In addition, for selected control system upgrades, so-called Software In Loop (SWIL) testing should be applied, making use of a medium/high fidelity plant process model (preferably configured to be plant-specific) in order to address the relevant closed-loop dynamics of performance over the full range of anticipated operational conditions and evolutions. Such an approach helps to ensures against field tuning and system modifications during plant startup & evolution to full power immediately following installation of the upgraded I&C system.

4.2 Design & Test Process Overview

With regard to specifics, the following provides an overview of elements expected to comprise sequential steps in the process:

a) Design Input Data Collection (Baseline Data)

This initial step involves collection and capture of relevant information utilized as a basis for control system design activities. The scope includes information about the process being controlled (and associated components/field devices), as well as the control system being replaced in retrofit applications.

b) Design

Utilizing a reference design as a basis, the intended control system functionality (algorithms & logic) is captured in the form of a Functional Requirements & Diagrams document specific to the project. This documentation, along with corresponding setpoints, serves the primary set of input to detailed design and implementation (i.e. configuration of application software database, logic sheets, and graphics)

c) Modeling & Analysis

In parallel with compilation of the above design documentation, a plant-specific plant process model is configured, including models of the control system(s) of interest and those associated with the scope of the upgrade.

This model is utilized to determine values of setpoints and tuning parameters that will provide desired system dynamic response and performance. Such analysis also serves to validate the design (algorithms & logic) relative to applicable performance criteria.

d) Testing

The above plant-specific models are interfaced with application software representing implementation of the systems of interest in order to exercise the application dynamically. Such testing dynamic demonstrates responses consistent with the intended design, thereby verifying proper implementation of the design. Following completion of the verification testing of the application software using the noted engineering model in SWIL test configuration, integration of the application into the operator training plant simulator takes place with corresponding testing.

e) Startup Support

After installation, operation of the upgraded system is observed in the context of a normal power ascension evolution, with selected test disturbances applied at operational plateaus.

The above steps have proven to be comprehensive and effective through application in many successful digital I&C upgrade projects.

5. SUMMARY

In summary, it is noteworthy that feedwater control has above all been a challenge historically within the nuclear industry in general, and within the US in particular, due to a number of factors enumerated above. Early efforts to address these challenges focused on mitigation, while later efforts progressed to system solutions in order to properly account for all relevant aspects of the problem. By extension, numerous digital I&C upgrades have been implemented for feedwater control, those most effective of which have been known to include an overall systems approach to incorporating enhanced design features through application of a structured process for design, implementation, and test. In relation to these upgrades, enhanced automatic control performance has been demonstrated in support of plant operational performance. The upgrades have been put in place through modifications implemented within typical outage windows, and have not resulted in impacts or delays in post-modification return to power. Most typically, there has been minimal field tuning of the upgraded systems, and there have been demonstrable reduction in operator burden while achieving enhanced operational performance.

6. REFERENCES

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