Control System Considerations for APR1400 integrated with Thermal Energy Storage

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1. Introduction

Global efforts for reduction of greenhouse gas emissions represent an opportunity for nuclear industry development. Nuclear Power Plants (NPPs) generate electric power characterized with one of the lowest carbon footprints among all available sources of energy. Therefore the technology aligns with current energy policy trends. Furthermore, NPPs are able to provide reliable electricity supply with very high capacity factors and competitive Levelized Cost of Electricity (LCOE). However, attempts to create low emission power systems which follow non-market based development of renewable energy sources generation often have resulted in challenges for other suppliers of electric power, including NPPs.

NPPs are primarily designed to operate at base load due to complex operation procedures and high-capital investment cost. The intermittent energy supplied from renewable energy sources can chaotically lower the wholesale prices of energy and in turn increase market demand for flexible power generation. One promising solution which would allow NPPs to adapt to new energy policies is high capacity Thermal Energy Storage (TES). The integration of TES with normal plant operation may provide an opportunity for NPPs to supply variable power output without reducing thermal output of the reactor.

Detailed analysis and design for a coupled TES installation is required in order to assure reliable plant operation. Previous analyzes have identified variation of plant operating parameters as a major challenge to NPP performance [1]. To address such challenges, design enhancements to Instrumentation and Controls (I&C) systems are proposed, changes which would limit the impact of introducing TES to plant operations.

Research presented here investigates proposed changes to the Korean Advanced Power Reactor with electric power output 1400 MW_e (APR1400) Power Control System (PCS) to accommodate new operating conditions resulted from integration with the Nuclear Heat Storage and Recovery (NHS&R) System previously described [1,2].

2. Background

The investigation reported here is a continuation of the work previously published. This previous focus related to steam and heat storage system design and optimization [1, 2].

2.1. APR1400 NHS&R System

The NHS&R System proposed for application to the APR1400 permits sensible heat storage and recovery, providing flexible output of the main Turbine Generator (T/G). A diurnal APR1400 NHS&R operation cycle is suggested with an upper bound extraction of 20% of Nuclear Steam Supply System (NSSS) thermal power, equivalent to 800 $MW_{t,}$ for 8 hours in the storage mode. Storage is followed by heat recovery operation with a thermal energy increment equivalent to 11% of NSSS power (422 MW_t). The recovered heat is assumed to be transferred to the secondary cycle for approximately 15 hours. The design objective is to maintain reactor power level constant while T/G ramp up and ramp down operations are performed.

During the storage mode of operation, Main Steam (MS) is transported to the Heat Storage Building (HSB) located adjacent to the APR1400 Turbine Building (TB). In the HSB, the heat is transferred to a tertiary cycle via shell and tube heat exchangers (Oil Heaters). The steam drains from the heaters are at high pressure and relatively high temperature. Therefore the condensate from the HSB is returned to the Deaerator (DA) to improve thermal performance of the overall thermodynamic system.

The stored heat is recovered by transfer to Feedwater (FW) in a facility named the Heat Recovery Building (HRB). A fraction of FW flow (~45%) is diverted downstream of the Main FW Pumps (MFWPs), reducing flow through the High Pressure (HP) Feedwater Heaters (FWHs). This diversion stream is heated in ‘recovery’ FWHs and returned and mixed downstream of FWHs No. 7. The proposed heat recovery configuration is illustrated in Fig.1.

The NHS&R System configuration was selected based on various cases analysis according to following criteria: (i) thermodynamic performance, (ii) impact on plant operation and hardware configuration, and (iii) installation cost.

The selected configuration is evaluated as superior due: (i) high round-trip efficiency (quantified as 80%), (ii) reduced extracted MS flow rate during storage mode operations, (iii) improved heat transfer process during heat recovery, (iv) simple hardware configuration, and (v) minimized number of modifications of existing plant Structures, Systems, and Components (SSC).

Final selection of the preferred TES technology it not critical to the research presented here. Hence the

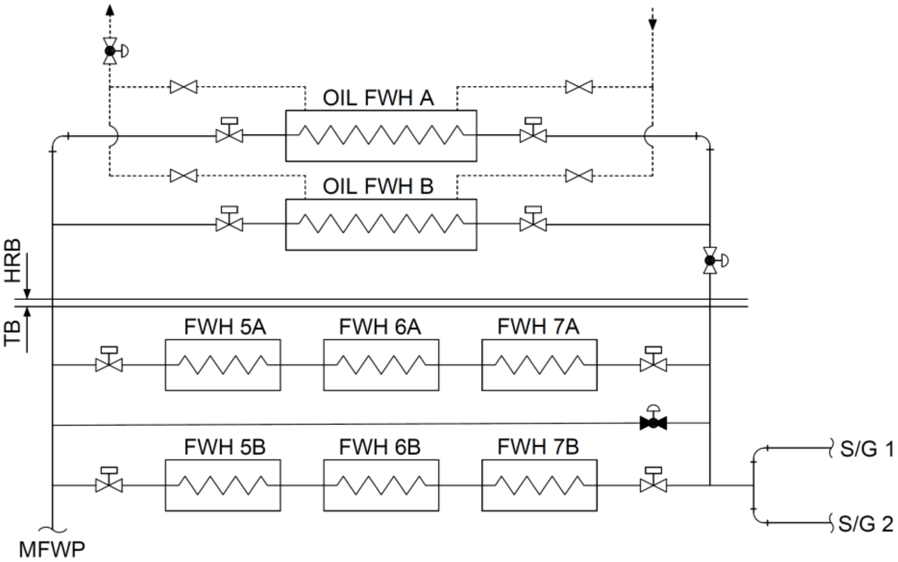

Fig. 1. APR1400 steam side heat recovery system configuration

detailed description of the NHS&R tertiary cycle is provided elsewhere [1].

2.2. The APR1400 Power Control System

The APR1400 I&C system for non-safety related systems is implemented by the Distributed Control System (DCS) platform. The platform constitutes an environment to conduct the following functions under normal operation: (i) operator interface, (ii) component-level control, (iii) automatic process control, (iv) high-level group control, and (v) data processing. Within the DCS platform, the PCS is implemented to integrate I&C systems responsible for reactor power level control. The following systems are incorporated into the PCS: (i) the Reactor Regulation System (RRS), (ii) the Digitalized Reactor Power Control System (DRCS), and (iii) the Reactor Power Cutback System (RPCS). Among these, the RRS is designed to automatically regulate reactor power in response to minor turbine load transients. The system aims to improve the load following capability of the NSSS.

A schematic diagram of the APR1400 RRS is provided in Fig. 2. The system receives as input signals: (i) the Reactor Coolant System (RCS) average temperature (T_{AVG}), (ii) the Turbine Load Index (TLI) and (iii) reactor power. T_{AVG} is calculated based on temperatures measured at hot legs and cold legs (T_{hot} and T_{cold}) in both loops of the RCS. TLI is determined based on the Turbine First Stage Pressure (TFSP), and reactor power as indicated by power range neutron flux monitors. The TLI the reference temperature (T_{REF}) program sets the desired average RCS temperature which is compared with the actual T_{AVG}. The resultant error signal is compensated by difference between indicated reactor power and the TLI. The RRS final output signal is fed to the Control Element Assembly (CEA) determining the CEA motion and rate. [3]

3. Analysis

The key impact of the proposed NHS&R system is APR1400 turbine cycle parameter variation under the storage and recovery operation modes. The evaluation here constituted the basis for further analysis of the APR1400 I&C System performance under plant modified operating conditions.

Analysis of the APR1400 plant assuming integration with the NHS&R System was performed by simulating steady-state conditions in the Performance Evaluation of Power System Efficiencies (PEPSE^{TM}) software. The model was simulated under storage and recovery operating conditions. Subsequently, results were compared with APR1400 heat balance diagrams under

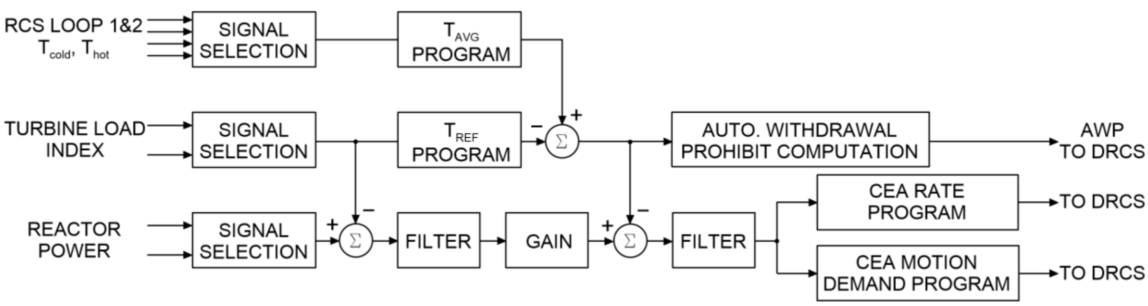

Fig. 2. APR1400 RRS block diagram [3]

Maximum Guaranteed Rate (MGR) and Valves Wide Open (VWO) operation.

APR1400 I&C system configuration is based on APR1400 Design Control Documents (DCD) available in the public record [3].

3.1. NHS&R impact on APR1400 plant operation

The primary constraint of the NHS&R System design is to minimize impact on the RCS. Therefore, analysis of the effects of NHS&R operation on the APR1400 secondary cycle is focused on screening for variable parameters directly affecting the RCS operation. The analysis indicates variation in Final Feedwater Temperature (FFT) as the primary concern.

For storage mode operations, heat equivalent to 800 MWt is extracted for the MS export to the HSB. This results in reduced mass flow rates and pressures throughout the turbine steam flow path. As a consequence, extraction pressures and flow, and hence heating is reduced. This lowers heating capability of the regenerative heating system leading to a reduction in FFT (see Table I.). Without operator action this would be expected to result in a reduction in T_{cold} followed by positive reactivity insertion to the core. To avoid this reactivity perturbation it is proposed that the operating pressure in the Steam Generator (S/G) be increase by adjusting the turbine Control Valve (CV) position. Proper adjustment of the S/G pressure can control the temperature of reactor coolant entering the S/G economizer section, and sufficiently maintain T_{cold} at a constant level.

Conversely, FFT is expected to increase under the APR1400 NHS&R heat recovery mode. Additional heat (422 MW_t) transferred to the FW results in a FFT increase. Without operator action, an increase in T_{cold} would be expected, reducing reactor power due to negative Coolant Temperature Coefficient (CTC).

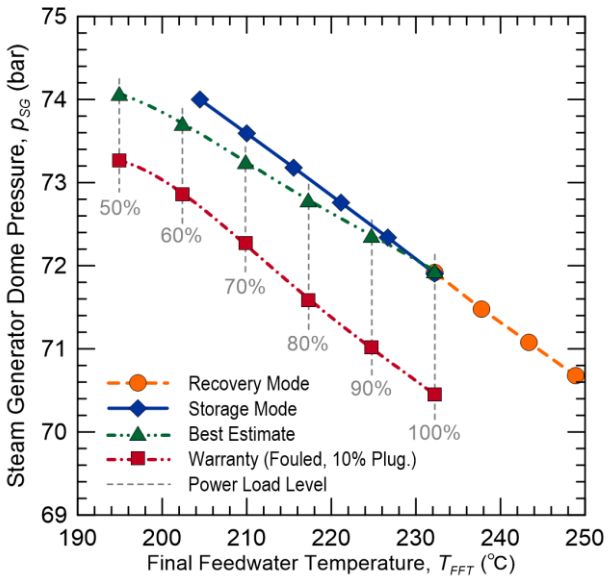

Fig.3. S/G dome pressure as a function of FFT.

Similar to the storage mode, for recovery, the FW temperature increase can be addressed by a decrease in operating S/G pressure. Under recovery, VWO operation sets the CVs to full open. Therefore it is proposed to lower the S/G pressure by first maximally opening the turbine CVs, and then adjusting the FFT temperature by flow regulation to the oil FWHs.

The process of S/G pressure regulation for FFT variation compensation was analyzed using Excel spreadsheet by numerical simulation of the APR1400 S/G performance. Fig.3. illustrates the estimated S/G pressure as a function of the FFT for Storage and Recovery operation. Note that the account was taken on maintaining T_{cold} at constant level 290.6 °C (555 °F). The 'Warranty' pressure curve corresponds to S/G dome dry steam pressure above steam dryers and the 'Best Estimate' curve indicates the pressure upstream from centrifugal moisture separators.

The key operating parameters of the APR1400 under various conditions described in this section are summarized in Table I.

Table I: APR1400 NHS&R main parameters under MGR, VWO, storage, and recovery operating modes.

Operation Mode	MGR	VWO	Storage	Recovery
Power Output, MW_e	1460.3	1518.2	1170.9	1586.4
Transferred Heat, MW_t	-	-	-800.0	422.0
FFT, °C	232.2	234.8	219.4	241.8
TFSP, bar	47.1	49.4	37.4	48.4
S/G pressure, bar	71.9	71.9	72.9	71.3

3.2. APR1400 I&C System Modification

Variable APR1400 turbine load (as indicated by TFSP) while operating at full power is not address in the current RRS design. The FFT variation results in need of S/G pressure regulation (see Fig.3.), what affects the TFSP what initiate CEA motion based on the pressure signal (TFSP) detected by the RRS.

The proposed solution to avoid reactor power variation and improve operability following integration with the NHS&R System is to modify the RRS to accommodate aforementioned changes.

Under storage mode operations, the TFSP decreases due to CVs regulation (for S/G pressure control) resulting in TLI drop. An additional indicator is suggested, termed here the Storage Load Index (SLI) to compensate for a 'false' reading per the TLI. The SLI is determined based on the calorimetric measurement of thermal power transferred to heat storage. To accurately measure condensate flow from the HSB it is

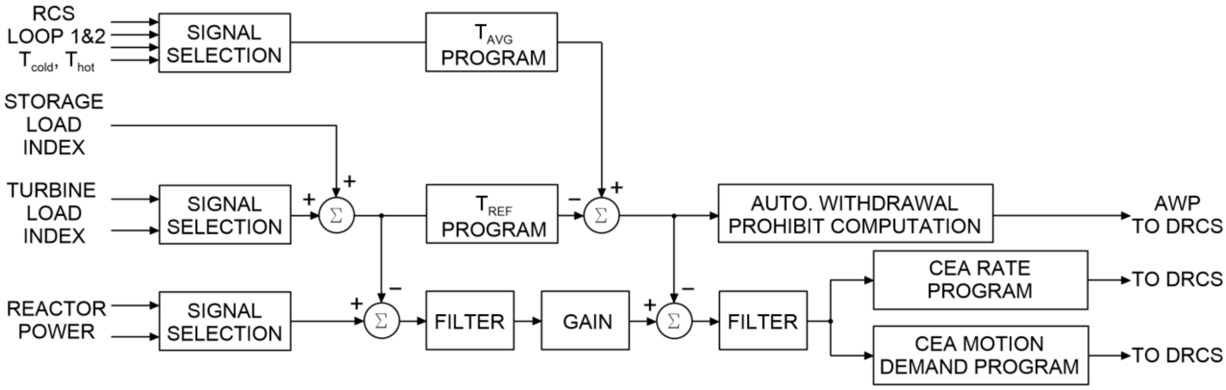

Fig. 4. APR1400 NHS&R modified RRS block diagram

recommended that ultrasonic flow meter be installed downstream of the oil heaters. The schematic block diagram illustrating the proposed modification is provided in Fig. 4.

Heat recovery operations are associated with a VWO High Pressure Turbine (HPT) CVs position and an increased MS mass flow rate resulting from increased FFT. These conditions lead to higher TFSP as compared to base load (MGR) operation. One solution to avoid a 'false' CEA motion demand signal is to take account of the higher FFT by calibrating the TLI program to reflect changes in the FFT. The FW temperature sensor should be located at sufficient distance from the FW return location to assure complete mixing of process flows in order to achieve a homogenous temperature distribution.

Note that heat recovered by FW recovery heating, and reduced flow to the primary FWHs results in a reduction of Extraction Steam (ES) supply. Therefore, additional mass flow throughout the turbine steam flow path are expected during recovery. Due to this, the impact on the HPT steam admission flow is related only to the increase in FFT.

4. Conclusions

In response to the shift in global energy policy, the nuclear industry needs to flexibly adopt measures to remain competitive. The technical and economic challenges of NPP flexible power supply can be addressed by TES technology.

Integration of NPPs with TES requires investigations of coupled system performance and of the impact on various plant systems. In particular, I&C System are expected to require design modifications. Analysis here investigates impact one of the APR1400 control subsystem, the RRS, for impact with NPP integration with the NHS&R System.

Thermodynamic analysis of the APR1400 NHS&R was performed by use of PEPSE^{TM} software. Results predicted FFT variation under different operating conditions. The proposed solution to address the impact on RCS temperatures is to regulate S/G pressure based on the value of FFT. Subsequent analysis identified this operation inconsistent with the current design of the APR1400 RRS system. The effect of S/G pressure regulation on the RRS performance was assessed.

Detailed analysis of the RRS system operation based on the APR1400 DCD provides a foundation for proposed modification to improve APR1400 operability while coupled with the NHS&R System. The recommended solution is to compensate the TLI signal with variously SLI indication under the storage mode, and the FFT measurement under heat recovery operation.

4.1 Future Work

Further analysis to assess the influence of the variation in MS flow rate to the second stage steam reheater on the RRS system performance is recommended. The heat balance analysis indicated variation of the mass flow rate in range of +/- 4% as compared to the APR1400 base load operation.

It is recommended that the present research be supplemented with further investigation of impact of the APR1400 integration with the NHS&R System on remaining control systems performance. Redesign considerations are suggested particularly in control systems integrated within the DCS Platform such as: (i) the DRCS, (ii) the RPCS, and (iii) the Steam Bypass Control System (SBCS).

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