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# Design Modification of Steam Bypass Control System to Maintain Reactor Power during Turbine Load Reduction Operation

Myung Jun Song*, Ji Hong Min, Ung Soo Kim
*269 Hyeoksin-ro, Gimcheon-si, Gyeongsangbuk-do, 39660*
**Corresponding author: smjun@kepco-enc.com*

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## 1. Introduction

The recent expansion of renewable energy sources has increased power generation and raised the need for reducing power of nuclear power plants to maintain grid stability. However, in domestic nuclear power plants, power reduction is performed manually by operators, increasing their workload and limiting the reactor's load-following capability. In addition, frequent reactor power changes require repeated boration and dilution, which generate large amounts of liquid radioactive waste.

If turbine power is reduced during normal operation, Control Element Assemblies (CEAs) are inserted by the Reactor Regulating System (RRS) to decrease reactor power in proportion to the turbine load reduction. The Digital Rod Control System (DRCS) should be set to Manual Sequence (MS) mode in order to maintain reactor power during turbine load reduction operation. If turbine power is reduced without CEA insertion, the reduced heat removal in the secondary system leads to a continuous increase in reactor coolant temperature. This temperature increase generates negative reactivity due to the moderator temperature coefficient and leads to a decrease in reactor power. Therefore, to maintain reactor power at 100% during turbine load reduction operation, the Steam Bypass Control System (SBCS) should be used to remove the excess energy from the Nuclear Steam Supply System (NSSS) in accordance with the amount of turbine load reduction.

In this paper, a modified SBCS logic has been developed to maintain reactor power at 100% during turbine load reduction operation, addressing the challenges of operator workload and liquid waste generation.

## 2. Design Modification of SBCS

### *2.1 Current SBCS*

The SBCS is designed to accommodate the load rejections of any magnitude including a turbine trip from full power without reactor trip. This is accomplished by substituting the Turbine Bypass Valves (TBVs) as a load on the NSSS whenever a large power mismatch is detected through the sensing of selected NSSS parameters such as steam flow, main steam header pressure, and pressurizer pressure. Thus the SBCS controls the TBVs to limit the reactor power/turbine load mismatch by dissipating excess NSSS energy. As shown in Fig. 1, the TBVs are modulated based on a comparison of the main steam header pressure to the setpoint. To enhance the load rejection capability of the SBCS, a quick opening of the valves is performed when the magnitude of load rejection exceeds the capacity of modulating control. Additionally, a rapid reduction in reactor power is performed through the Reactor Power Cutback System (RPCS) if the magnitude of the load rejection exceeds the SBCS turbine bypass capacity. In this manner, a full load rejection can be accommodated by the TBVs and RPCS.

The SBCS operates in two automatic modes: Remote Auto and Local Auto. The Remote Auto mode uses programmed setpoints during normal operation. Quick opening and RPCS signals are only active in this mode. The Local Auto mode is a control mode primarily used before turbine synchronization, in which operators adjust the setpoint to maintain reactor coolant temperature.

### *2.2 Modified SBCS*

During turbine load reduction operation, the pressure increase in the secondary system should be minimized in the event of additional transients such as load rejection or turbine trip. Accordingly, the SBCS should be operated in Remote Auto mode, and it is necessary to generate quick opening and RPCS signals to prevent reactor trip during these transients. Fig. 1 shows the conceptual control logic of the modified SBCS designed to complement the NSSS control systems so as to extend the load following capability of the NSSS. In Fig. 1, the blue region represents the current SBCS logic, while the orange region indicates the modified SBCS logic designed for turbine load reduction operation.

In order to maintain reactor power at 100% during turbine load reduction operation, a separate SBCS setpoint program for load reduction is implemented as shown in Fig. 1. This setpoint is determined to maintain secondary pressure at the level corresponding to 100% reactor power. When the turbine load reduction operation is not conducted, the current SBCS logic remains in service. Therefore, a dedicated "Mode Selector" function is required to switch between different SBCS setpoint programs based on operating conditions. In other words, when performing turbine load reduction operation, as illustrated in Fig. 1, the operator selects "Reduced Power Operation" on the SBCS Mode Selector. This activates the dedicated SBCS setpoint program for load reduction instead of the current setpoint program and automatically switches the DRCS to MS mode to maintain reactor power at 100%.

The design modification of the SBCS logic, as shown in Fig. 1, enables automatic turbine load reduction while maintaining reactor power, thereby reducing operator workload. Even if transient events such as load rejection or turbine trip occur during turbine load reduction operation, the modified SBCS logic remains in Remote Auto mode and allows activation of the quick opening and RPCS signals to prevent reactor trip. Furthermore, as CEA insertion is required for reactor power reduction during the transient events, the DRCS is automatically transitioned to Automatic Sequential (AS) mode.

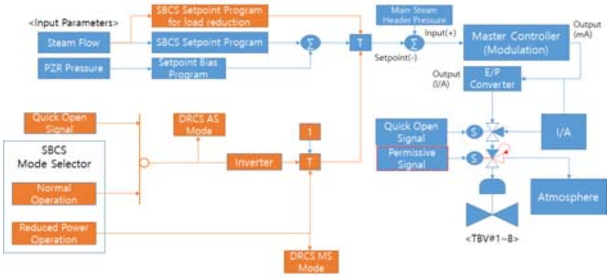

Fig. 1. Conceptual control logic of the modified SBCS for turbine load reduction operation

## 3. Simulation Results

To assess the effectiveness of the modified SBCS logic, turbine trip event was selected and computer simulations were performed using the KEPCO E&C Integrated System Performance Analysis Code (KISPAC) which had been used in plant performance analysis.

### *3.1 Simulation Code*

The KISPAC is a best-estimate nuclear power plant simulation tool which is designed to analyze the thermal-hydraulic responses of the NSSS and major secondary systems during non-loss of coolant accident transients, power range transients, reactor trips, plant heatup and plant cooldown [1]. Major systems modeled in detail include the reactor coolant system, the main steam system, and the main and auxiliary feedwater systems. Other systems which influence the response of the major heat transport systems are also modeled. These include the chemical and volume control system, the safety injection system and a limited turbine system model. Plant monitoring, control and protection systems, including instrument lag time and instrument decalibration due to environmental effects are also modeled. In addition to the fluid system modeling, the KISPAC code includes detailed models for all NSSS control systems for APR1400 [2] including FeedWater Control System (FWCS), SBCS, RRS, Pressurizer Level Control System (PLCS), Pressurizer Pressure Control System (PPCS), and RPCS.

### *3.2 Results of Turbine Trip Event*

During normal operation, the RPCS is actuated above 75% reactor power and the third main feedwater pump is operated above 70%. To maintain the same RPCS operation and number of main feedwater pumps as in 100% power operation, the modified SBCS logic is determined to be applied within the 100–80% power range. A turbine trip is simulated at 80% turbine power while maintaining reactor power at 100%.

Reactor power (the solid line in Fig. 2) is maintained at 100%, while turbine power (the dashed line in Fig. 2) decreases from 100% down to 80%. To accommodate the reduced turbine load while maintaining reactor power at 100%, the TBVs automatically open to remove excess energy in the secondary system by increasing the steam bypass flow, as indicated in the dotted line of Fig. 2. When a turbine trip occurs at 100% reactor power while turbine power is at 80%, all TBVs are quickly opened by the SBCS. The reactor power is adequately controlled by the RPCS and RRS. The RPCS drops regulating CEA group 5 or 5+4 to reduce the reactor power quickly. The RRS gradually reduces the reactor power to the CEA Automatic Motion Inhibit (AMI) setpoint of approximately 50% (the solid line in Fig. 3), which corresponds to the turbine bypass capacity, such that all automatic CEA motions are blocked. The rapid decrease in steam flowrate from the steam generator due to the turbine trip causes a large disturbance in the steam generator pressure, which increases sharply until the SBCS initiates excess steam dumping (the dotted line in Fig. 3). The rapid increase in steam generator pressure (Fig. 4) causes the steam generator level to shrink. After the initial shrink, the steam generator level recovers slowly to the setpoint of 50% via the FWCS (Fig. 5). Other NSSS control systems respond to the plant transient and successfully maintain all plant parameters within acceptable ranges, thereby preventing any reactor trip.

In the absence of the quick opening and RPCS signals during a turbine trip, a reactor trip due to high pressurizer pressure occurs (Fig. 6). In this figure, the solid line represents the scenario in which quick opening and RPCS signals are generated, while the dashed line corresponds to the case without such signals. Therefore, the SBCS is required to remain in Remote Auto mode during turbine load reduction operation.

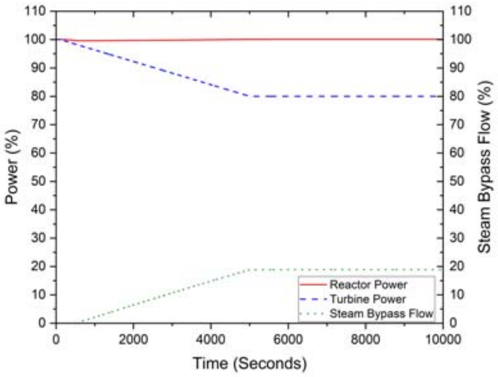

Fig. 2. Reactor power, turbine power, and steam bypass flow during a turbine load reduction from 100% to 80%

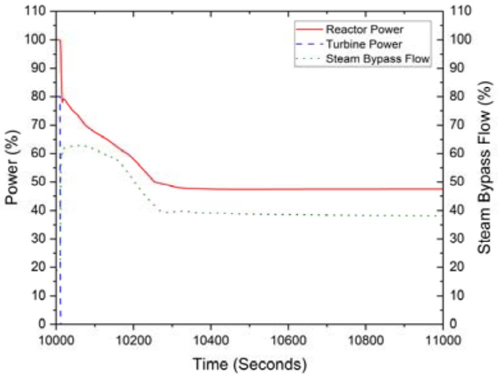

Fig. 3. Reactor power, turbine power, and steam bypass flow during a turbine trip

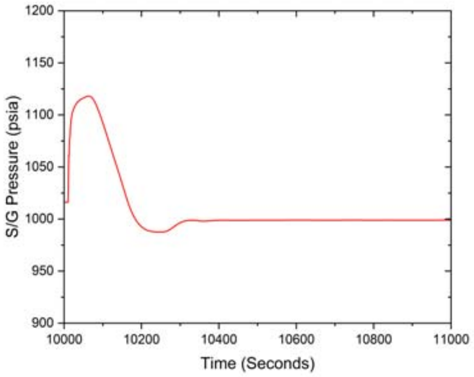

Fig. 4. Steam generator pressure during a turbine trip

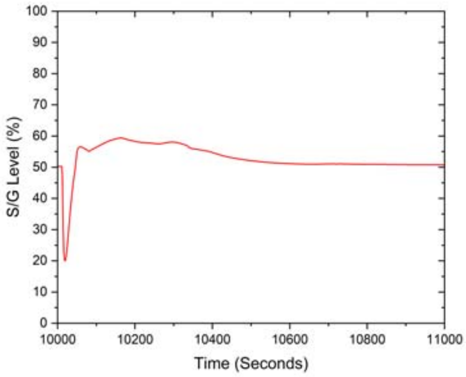

Fig. 5. Steam generator level during a turbine trip

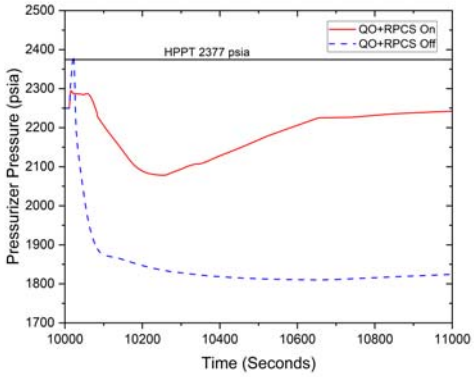

Fig. 6. Pressurizer pressure during a turbine trip

## 4. Conclusion and Further Evaluation

A modified SBCS logic has been developed to maintain reactor power at 100% during turbine load reduction operation. The results demonstrate that no reactor trip occurs during a turbine trip event at 80% turbine power, even when the TBVs are open and reactor power is maintained at 100%.

The application of the modified SBCS logic introduces several operational and mechanical challenges that require further evaluation. These include increased wear of TBVs, condenser nozzles, tubes, and spargers due to higher steam flow during turbine load reduction operation [3]. Economic trade-offs should be evaluated because maintaining reactor power increases fuel costs, whereas reducing reactor power leads to frequent CEA movement, higher liquid waste generation, and increased operator burden. A cost-benefit analysis is required before implementation of the modified SBCS logic. Furthermore, the development of a district heating system that utilizes extracted steam from the turbine during turbine load reduction operations for process heat or district heating applications is necessary for nuclear power plants.

## REFERENCES

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