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DEVELOPMENT OF THE DIGITALIZED AUTOMATIC SEISMIC TRIP SYSTEM FOR NUCLEAR POWER PLANTS USING THE SYSTEMS ENGINEERING APPROACH

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The automatic seismic trip system (ASTS) continuously monitors PGA (peak ground acceleration) from the seismic wave, and automatically generates a trip signal. This work presents how the system can be designed by using a systems engineering approach under the given regulatory criteria. Overall design stages, from the needs analysis to design verification, have been executed under the defined processes and activities. Moreover, this work contributes two significant design areas for digitalized ASTS. These are firstly, how to categorize the ASTS if the ASTS has a backed up function of the manual reactor trip, and secondly, how to set the requirements using the given design practices either in overseas ASTS design or similar design. In addition, the methodology for determining the setpoint can be applied to the I&C design and development project which needs to justify the error sources correctly. The systematic approach that has been developed and realized in this work can be utilized in designing new I&C (instrument and control system) as well.

KEYWORDS : Automatic Seismic Trip, Reactor Trip, Seismic Instrument

1. INTRODUCTION

Damages from the offshore Tohoku earthquake of March 11, 2011 was on a scale beyond our imagination. Through this horrific event, we have learned how a disaster can adversely affect people and country and how serious the result would be, if the earthquake event triggers a nuclear power plant (NPP) accident. Even though the accident initiated by an earthquake induced tsunami, the station black-out amplified the severity. As a result there is a need for counter measures for the potential risk from earthquakes to be emphasized.

Historically, the Korean peninsula has been stable and it has a low likelihood of a severe seismic event, with very few questions on earthquake induced fatalities being seriously discussed. In July 2007, Kashiwazaki-Kariwa NPPs in Japan were damaged by a severe earthquake of magnitude 6.8. It is remarkable that this was the first occurrence of the integrity of NPPs being compromised by a severe earthquake that exceeds the operating basis earthquake (OBE). From the lessons learned in the Japanese case, the Korean government has raised the need for an automatic reactor trip system to be considered for both NPP safety and public acceptance. Moreover, the earthquake induced tsunami in 2011 that brought about the core meltdown and hydrogen explosion in the Fukushima NPPs makes an automatic seismic trip system (ASTS) an essential system for preventing a disaster at NPPs.

Figure 1 illustrates the design process for the digitalized ASTS. The four (4) rounded rectangular boxes represent the stages for the process and the text box under each stage contains the identified activities to be performed during each stage. The design work was completed when the design verification was finished. Beyond these processes, the implementation, test, verification and validation work followed on the right leg of V-model, but this is not shown in this diagram, below.

In order to analyze the needs, the lessons learned from Japan and Taiwan were investigated. They have installed a ASTS as one of the counter measures for earthquake induced accidents, so a study of their system would be the good initiation point of the research. Throughout the needs analysis, the performance and function were identified.

The next stage was the requirements analysis. This was the starting point of problem solving therefore, making complete and correct requirements was essential work at this stage. Specifically, the licensing and user requirements

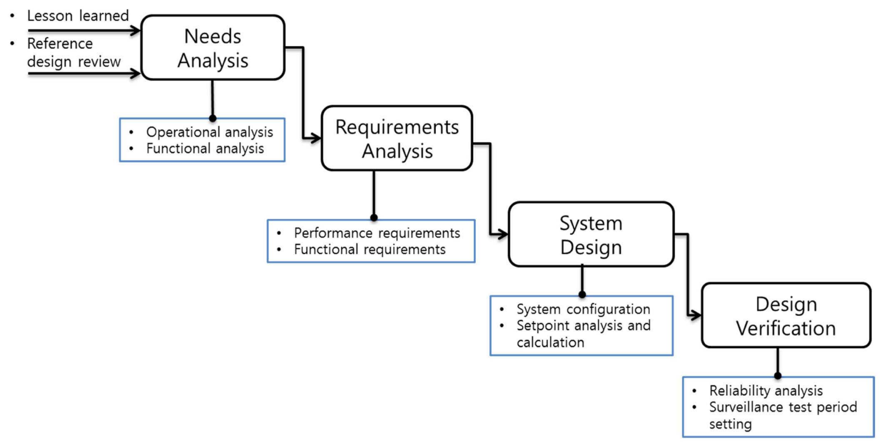


Fig. 1. ASTS Design Stages

were the basis of this work. The third stage was the system design. To decide the configuration of the system, not only the dedicated sensing and coincidence part of the ASTS, but also the trip initiation circuit should have been investigated. In this stage, logic drawing was also developed. The final stage was to verify the design. As verification measures, the system reliability and availability are selected. The design input was taken from the reference design experience. In this case, the operating NPP design data was brought into the verification work.

By adapting a systems engineering approach into the ASTS design, we could get a broad perspective of the design in the incipient stage. The process and activities to be performed were identified before the needs analysis stage. Through this approach, the schedule and investment could be optimized. It took around one year for system design. It was quite short period of time to design the system considering it had a new operational and functional concept.

2. NEEDS ANALYSIS

Figure 2 shows how needs are analyzed. The diagram is redrawn using needs analysis flow diagram of A. Kossiakoff et el [1]. This stage begins with analyzing the need for an ASTS. Most predecessor designs have been designed to trip the reactor by actuation of the reactor trip system (RPS). It means that the ASTS gives an extra trip parameter to the RPS. There were some limitations in the system not to introduce the unqualified system. In addition, the predecessor systems which were developed by Japan, Taiwan, and USA, have been used analog system but it became obsolete. The need to decide the trip logic is the other essential part of analysis. The predecessor systems have a RPS trip function, but it decreased the availability of the system including pseudo reactor trip possibility. Table 1 shows a SWOT (strong, weakness, opportunity and threat) analysis result of the predecessor system.

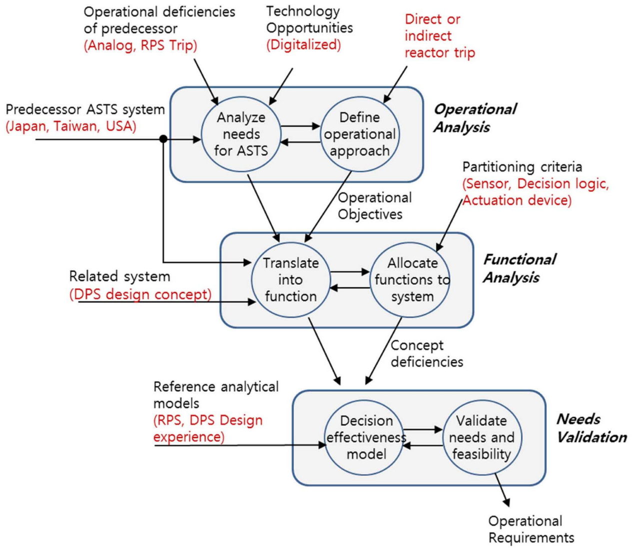


Fig. 2. Process and Activities of Needs Analysis Stage (Where, DPS: Diverse Protection System, RPS: Digital Reactor Protection System)

Table 2 shows the technical opportunity of the alternative design. It is based on the digitalized hardware system. Since Korean NPP systems are designed and developed by digitalized systems, the stages and process are well established. However, the digitalized ASTS has concerns of not having reference design. One more item to be analyzed is the introduction of the indirect trip function as a DPS (diverse protection system).

The second process to be performed is the functional analysis. As shown in figure 2, the needs and operational approach of the ASTS are used as the input to decide on the function.

The International Atomic Energy Agency (IAEA) had called a meeting on the advisability of an the ASTS in April 1995. Throughout this meeting, the recommendation was raised as [2];

Table 1. SWOT Analysis Result of Predecessor System

Limitation of predecessor system	Strength	Weakness	Opportunity	Threat
Analog system	Experienced	Obsolescence	Reducing design work	Decrease system reliability
RPS trip	Easy to design	License ability	Trip possibility	Plant availability

Table 2. SWOT Analysis Result of Alternative Design

Limitation of predecessor system	Strength	Weakness	Opportunity	Threat
Digitalized system	Modernization	Inexperienced	Availability and Reliability	Increase hazard level
Indirect reactor trip	Licensing unnecessary	Proven by quantitative manner	Plant availability	Possibility of failure of reactor trip

Table 3. ASTS Design Characteristics of Three Countries

Nation	Background of ASTS	Basis for Setpoint	Sensor installation	Trip circuit	Safety class	System type
Japan	Mandated by MITI Ordinance 62	120gal (before 2006, 0.9S1)	Free field	Reactor trip Switchgear	Safety	Analog
Taiwan	Recommend from nuclear authority	OBE's ZPA-0.05g				
USA	Optional	OBE				

- It is preferable to install an ASTS at a high seismicity site such as Japan and the west bay area of America where high seismic hazards are estimated. However, if the confidence about the NPP safe operation, such as credit for the operator action during an earthquake, or the public acceptance is low, then the installation can't be considered.
- Trip setpoint can be set in consideration of both the hazard level and the SSE level of the specific NPP. The OBE can be used as the system trigger level. The reactor trip must be taken place prior to the maximum seismic level.

In this meeting, the potential disadvantages of the ASTS were pointed out [3]. Even though the PGA exceeded the OBE level, if the frequency of the wave is over 17Hz, it doesn't cause serious damage to the NPP. One more fact that we have to notice is the duration of the earthquake. In general, the duration is shorter than two (2) seconds. Those discussions were a good starting point of the design.

For elicitation of the requirements, the currently available systems from Japan, Taiwan, and USA were reviewed. Table 3 shows the characteristics of the system design from those three countries. They preferred to add one more trip parameter into the existing RPS (reactor protection system).

As seen in Table 3, Japan mandates a ASTS by the Ministry of International Trade and Industry (MITI) order 62 [4]. Before the Niigata Chuetsu-oki earthquake in 2007, MITI recommended to use 0.9S1, where S1 is the maximum design earthquake, for the trip setpoint, referencing the JEAG (Japan Electric Association Guideline) 4601 criteria [5]. But the NSC (Nuclear Safety Commission) has changed the trip setpoint incorporating the lessons learned from the Niigata earthquake. The revised setpoint is set at 120 gal.

Taiwan nuclear authority requested to install the ASTS in all six existing NPPs after the disastrous Chi-Chi earthquake. The scram level was set to OBE ZPA (zero period acceleration) minus 0.05g. The OBE ZPA level is obtained from the range of 0.1Hz to 10Hz.

In the USA, only two plants in California have installed the ASTS. They are Diablo Canyon and San Onofre. These installations were not because of the USNRC's regulation, but for the ACRS (advisory committee for reactor safety) concern. This was because the qualification level of the main equipment was beyond the revised SSE level due to newly found Hosgri fault.

Until 2012, the Korean NPPs used the manual reactor trip function to cope with seismic events. When an earthquake level is over the OBE, the operator is obliged to trip the reactor, then a walkthrough is mandated to check the integrity of the plant. The clients' needs were rooted from this background. Therefore, the needs were extracted that the ASTS should not increase the possibility of loss of electricity generation while it satisfies both the safety and public acceptance. This somewhat contradictory need must be accomplished. Consequently, the concerns have been raised on how we can satisfy those needs and control the overall cost, because, total 20 units were scheduled to be equipped with this additional system during their overhaul outage period by the end of 2012.

As the reader can acknowledge, the requirements from the client were somewhat different from the reference systems. The NPP wanted an indirect trip system to support the operator's manual action. If operator should be unable to trip the reactor, then the ASTS can back up the lost action of the operator. While those three reference systems shown in Table 3 are signified to add one more reactor trip function, the Korean NPPs want a standby trip function to support the operator's behavior.

Figure 3 shows the process for needs validation. Similar to the design of predecessor systems, the ASTS can be categorized into three pieces; they are sensor module, system hardware for decision logic, and the final trip circuit. In this process, the alternative design is compared with the predecessor design. In terms of the sensor module design, the measures to decide the design are cost, schedule and performance. The second category is the system hardware. The alternative, which is configured with digitalized hardware, is compared to the analog based hardware by measures of reliability, availability and maintainability. Lastly, the ability to license and the operability are used to select the trip initiation circuit. To analyze these measures, the experience data is applied from the reference system of the operating NPP. They are RPS and DPS.

3. REQUIREMENTS ANALYSIS STAGE

3.1 Top-tier Requirements

Using the given needs, the system concept is set in order to explore whether the needs could be converted into the requirements without contradicting with current regulation guidlines. As conclusion it was found that the system that has a supporting function could be categorized as non-safe. For this reason an ASTS was designed to satisfy the Korea Institute of Nuclear Safety (KINS) regulation guidelines for instrumentation and control (I&C) system 8.1 [6].

Although an ASTS wouldn't be implemented in the safety system, the other concern about what seismic category must be applied to the design. Engineering judgment made it simple work in that the system would be operated under the SSE environment. It should be seismic category I, where category I is defined by USNRC as; structures, systems, and components that are designed and built to withstand the maximum potential earthquake stresses for the particular region where a nuclear plant is sited [7].

In addition, we decided on the adequacy of performing the environmental qualification for the system, in consideration of the postulated condition during or after the SSE. The last concern was about the software class because major functions will be implemented by the software. After lengthy discussion, a decision was made to apply the class of "important to safety". The equivalent class of software integrity is level 3 from IEEE 1012 [8].

As a result, we attained the top-tier requirements to fulfill the licensing issues as depicted in Table 4. As shown, the typical safety issues such as single failure criterion, defense in depth and diversity are not applied as intended.

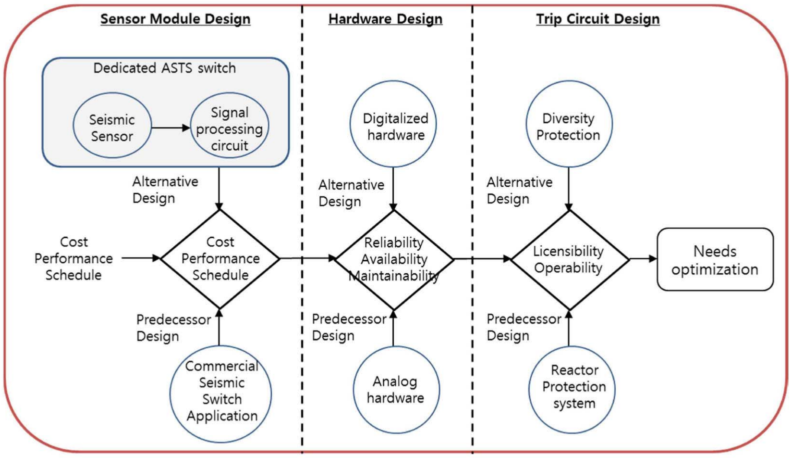


Fig. 3. Process for Needs Validation

In conclusion, ASTS has two contradicting top-tier requirements; to not increase the possibility of loss of electricity generation while it satisfies both the safety and public acceptance.

3.2 Performance Requirements

The next step was regarded to draw performance requirements which specify the technical, operation, and safety of the system. Time to scram, uncertain requirements, system availability and reliability requirements were included in this category. Table 5 shows the performance requirements for the ASTS.

The time to scram the reactor needs to be compared with the expected duration of the earthquake. Automatic scram is utilized to initiate reactor trip before the maximum earthquake. Typically, damages from the strong motion of the earthquake are diminished within 2 seconds [9]. Therefore, the dead band of the channel is set to 10 seconds. When a strong earthquake is incident to an individual channel, the bistable logic generates a trip signal and latches onto it for 10 seconds. After 10 seconds, it is released automatically.

The system accuracy is set to ±5% on reflection of our design experiences and information from the INER (Institute of Nuclear Energy Research) in Taiwan [10].

Even ANSI/ANS 2.2 [11], a criterion for the earthquake instrument, offers the surveillance interval but there is no criterion for the ASTS. Therefore, the reliability analysis from the sensor to the ASTS output channel should be conducted to know the surveillance test interval. The initial reliability target for 6 months and 18 months are set as 0.99 and 0.95 respectively if the PLC (programmable logic controller) is applied.

3.3 Functional Requirements

During the design, the concern was raised on how we can reduce the possibility of spurious trips in order to satisfy the customers' needs by not interrupting electricity generation. The backup data has been collected and analyzed.

Experience has shown that the strong motion of the earthquake comes from lower frequencies below 10Hz. Figure 4 displays a cross plot of the corner frequency (fc) versus seismic moment (lower scale) and moment magnitude

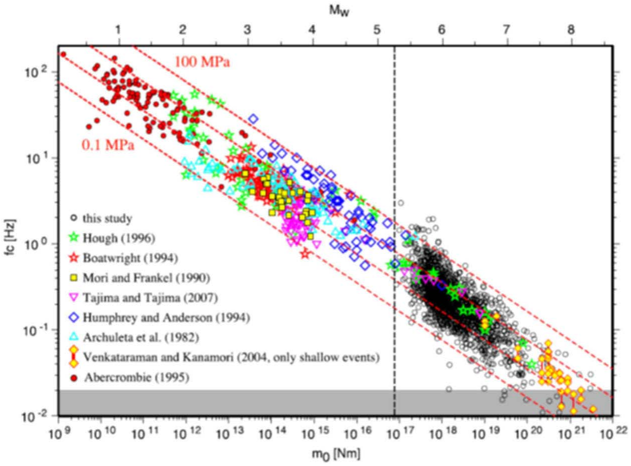


Fig. 4. Frequency Versus Seismic Moment (Lower Scale) and Moment Magnitude (Upper Scale) (Almann and Shearer)

Table 4. Top-tier Requirements

Items	Features	Remarks
Safety grade	Non-safe	KINS regulation guide for I&C system 8.1
Actuation device	Load center	MG control panel
Single Failure Criterion	Not applicable	
Environmental Qualification	Applicable	Normal and anticipated operational occurrences.
Seismic Category	Category I	
Defense in Depth and Diversity	Not applicable	
Software Class	Important to Safety	Safety integrity level 3 per IEEE1012-1998

Table 5. Performance Requirements

Requirements	Value	Remarks
Time to Scram	Dead band of 10 Sec	Trip output from the comparator is maintained for 10 second.
Uncertainty	±5%	From sensor to PLC output
Unavailability	10^{-6} failure/demand	
Reliability	6 months 0.99 18 months 0.95	if PLC system is applied

(upper scale) [12]. In this figure, the major energy band tends to move to the lower frequencies. In other word, when the magnitude is getting higher, the frequency is getting lower. The frequency over Mw=5 is below 2Hz in this figure.

The frequency of seismic waves occurring in the eastern part of the USA exceeded the 15 Hz was relatively short, around two seconds. Consequently it has no impact on the safety integrity of the NPPs [13]. The IAEA joint meeting [14], concluded that the high frequency acceleration did not induce damage to components. For this reason, they decided to use an acceleration amplitude between 2-8 Hz to exceed the OBE criteria. According to the EPRI report [15], the peak spectral acceleration, averaged between 2Hz and 10Hz, is a reasonably consistent threshold for damage (i.e., conservatively defined at MMI greater than VI). Therefore, we could conclude that the frequency acceleration over 10Hz does not induce damage to the safety related equipment.

The experience in Korean NPPs also proves that the pseudo seismic signal is distinctive over 10Hz while the triggered signal shows low frequency characteristics below 10Hz. Figure 5 shows the spectrum of pseudo seismic waves which were detected by the SMS (seismic monitoring system) in NPPs. These spectrums were captured from the ECCS (emergency core cooling system) pump and lightening. When the pump starts, the cavitation generates the shock and then it propagates to the seismic sensor and then the sensor is triggered. Lighting is also the source that generates the shock wave to trigger the sensor. Including these signals, many other cases showed that the distinctive frequency from the pseudo seismic signal was found to be over 10Hz.

Using this background, we decided to cut-off high frequency over 10Hz. In this case, a special filter which fulfills both the stability and the sharpness is required.

To keep the unavailability target, the system should be implemented by the digitalized system. The digitalized system has lower unavailability than the analog system. The target value is set to about the same as the digitalized safety system.

Beyond these design features, the energized trip function, and two out of four (2/4) comparator logics are applied. Moreover, the ASTS is designed to permit the channel bypass during the test. Those measures are set in order to cope with an unplanned trip.

The reliability target is set as; 0.99 for 6 months and 0.95 for an 18 months surveillance period. Table 6 depicts the distinctive functional requirements that are different with the reference design from Japan, Taiwan and USA.

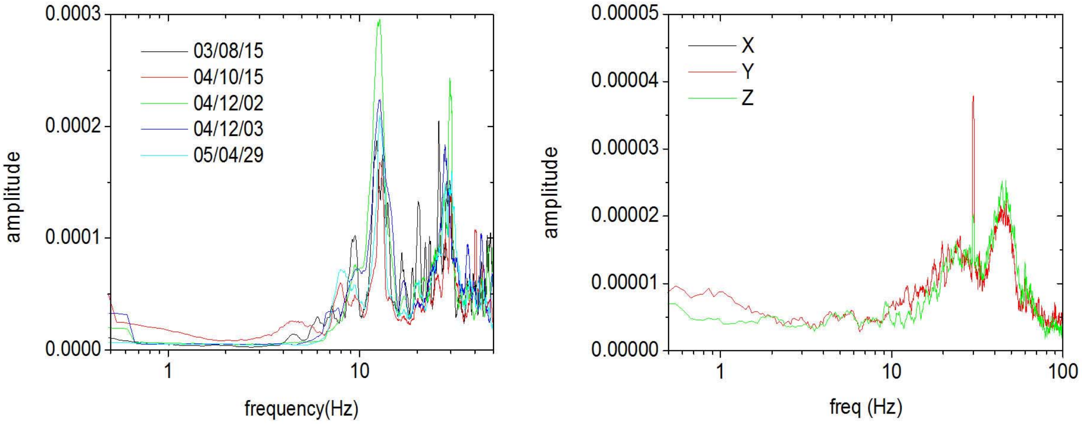


Fig. 5. Pseudo Seismic Wave Detected by the Seismic Sensor (a) Spectrum by the ECC Pump Starting (b) Spectrum by the Lightening.

Table 6. Functional Requirements (Distinctive)

Requirements	Means	Remarks
Digitalize the channel	From bistable logic to the output channel	Trip output from the comparator is maintained for 10 seconds.
Block spurious trip	Apply 10Hz lowpass filter	Requires stability and the sharpness of the filter
Do comparison	Apply two out of four logics	Apply four sensors
Do trip actuation	Cut-off power paths into RTSG	Permit channel bypass
Trip when the channel is energized	Energize thetrip	Allow trip bypass

4. SYSTEM DESIGN

4.1 System Configuration

As shown in Figure 6, the seismic signal detected by the accelerometer is filtered, rectified, and converted to current. The sensor module cuts off the frequency range over 10Hz in order to pick out the strong motion of the earthquake. The seismic signal has positive and negative portions, which is why the rectifier circuit is added. The rectifier converts a bipolar signal to unipolar.

The overall scheme of the digitalized ASTS is shown in Figure 7. The sensor output is interfaced with digital input card at the ASTS cabinet. The decision logic is set as two out of four, but the system is composed of two independent channels. They are N1 and N2. For isolation between channels the digital input/output cards are applied. The dotted line on the ASTS cabinet is the scope of the trip logic channels N1 and N2. The ASTS cabinet is implemented by a digitalized system, such as the PLC (programmable logic controller), the FPGA (field programmable gate array), or the DCS (distributed control system). The bistable and decision logics are configured with software inside each channel.

The operational principles are as follows. When the measured signal exceeds the set-point, the edge triggering happens and the status is set to "0" by comparator actuation. In this case, the latch is engaged due to the edge triggering, and keep this status for ten seconds. The purpose of the 10 second latch is to synchronize the individual channel for the coincidence logic. If the signals are not properly synchronized, the trip initiation signal may not be actuated during a strong earthquake. The ASTS consists of four (4) diverse channel applications. The bistable signal from each channel feeds into 2-out of-4 coincidence logics for generating a trip initiation signal.

The reactor is tripped by a cutoff in the MG set power to the control rod drive mechanism (CRDM) as shown in Figure 8 (a), while (b) presents the overall logics of the ASTS. As shown, it triggers the power from the MG set to the RTSS by opening the breaker.

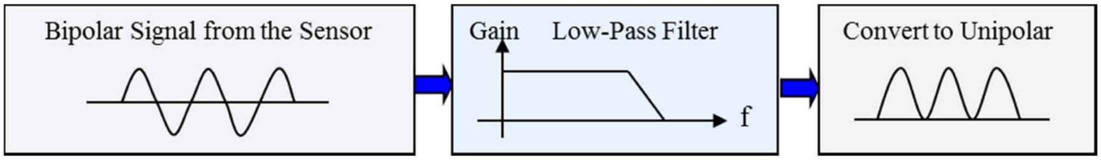


Fig. 6. Conceptual Diagram of Sensor Module for Signal Processing.

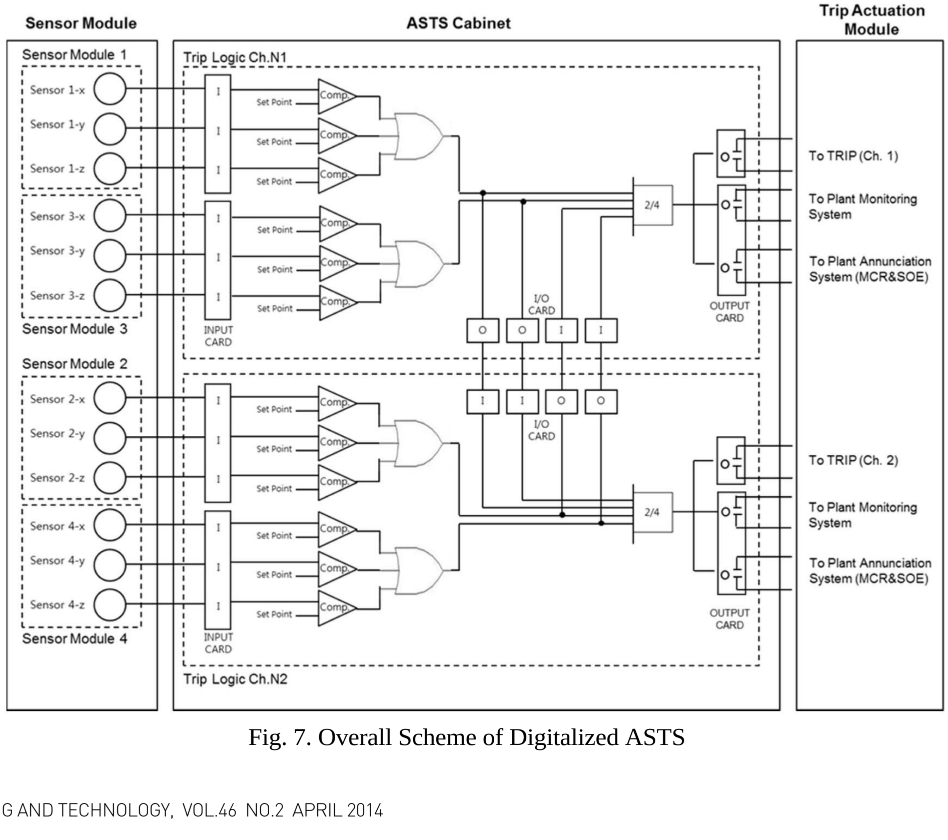


Fig. 7. Overall Scheme of Digitalized ASTS

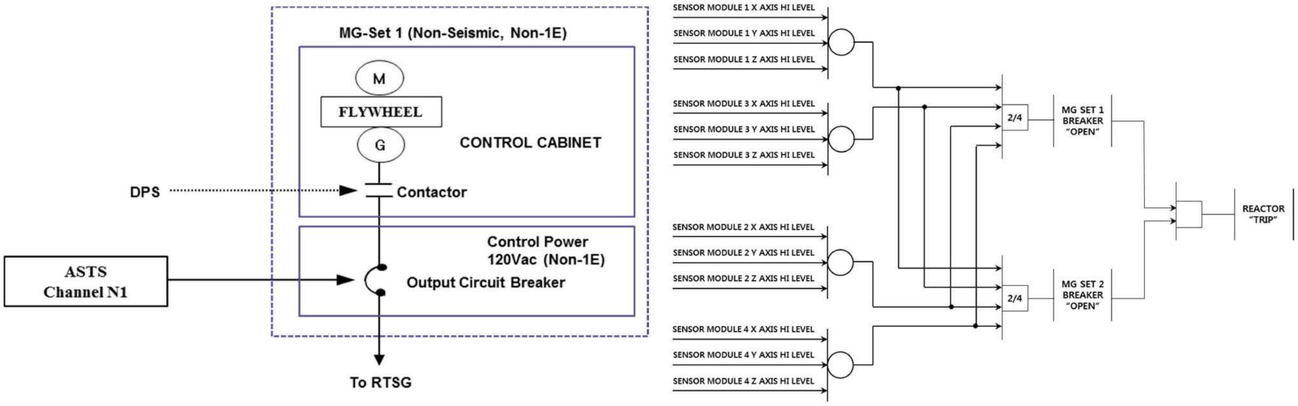
4.2 Setpoint Analysis

Generally, the ASTS trip setpoint can be set based on either the OBE level, or the SSE level. The reason to set the trip value to the OBE level is for the functional integrity of safety related systems, structures, and components (SSC). When we set the trip value close to the SSE, the SSC integrity may not be secured. Consequently care must be taken not to exceed the SSE level. In this work, the trip set-point is determined in the range from OBE to SSE while considering both safety and availability of the plant.

Figure 9 shows how the ASTS trip set-point is calculated. In this figure, the measured vibration motion of NPPs is regarded as equivalent to the movement of free-field seismic stations.

Reg. guide 1.60 determined the DRS (design response spectra) representing the effects of the vibratory motion of the SSE and the OBE on sites underlain by either rock or soil deposits and covering all frequencies of interest. The DRS, specified for design purpose, can be developed statistically from response spectra of past strong-motion earthquakes [16]. The time history should be converted from the given DRS. In this case, the computed 5% damped response spectrum of the artificial ground motion time history shall not exceed the target response spectrum at any frequency by more than 30% in the frequency range of interest [17].

Figure 10 shows the comparison of the artificial ground motion time history from RG 1.60 and the target response spectrum in the range of 0.1Hz to 40Hz.



(a) (b)

Fig. 8. Scheme of ASTS (a) One Channel Trip Circuit (b) Trip Logic

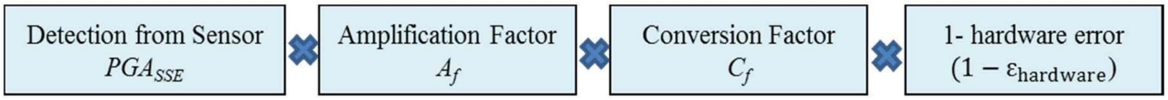


Fig. 9. Conceptual Illustration for Calculating ASTS Trip Set-point [7]

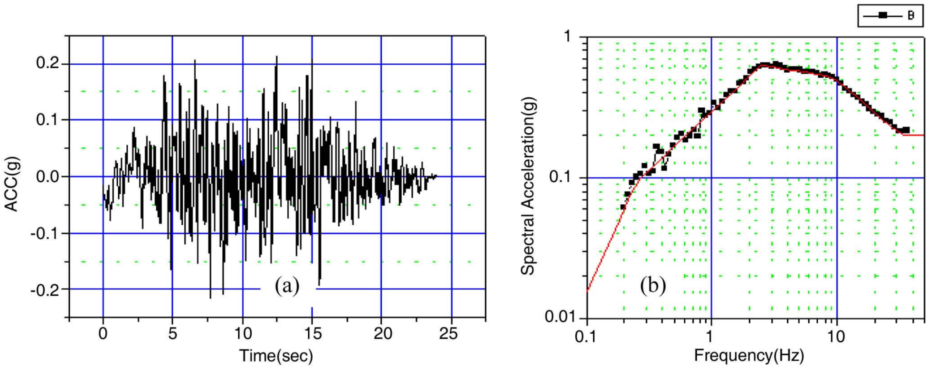


Fig. 10. Comparison of (a) Time History and (b) Target Response Spectrum

Equation (1) expresses the method to obtain the ASTS trip set-point. For calculating the ASTS set-point, the PGA value at SSE, conversion factor, amplification factor of the sensor location and the ASTS hardware error must be considered.

$$\mathrm{SP_{ASTS}} = \mathrm{PGA_{SSE}} \cdot \mathrm{C_f} \cdot \mathrm{A_f} \cdot (1 - \varepsilon_{\mathrm{hardware}}) \qquad (1)$$

Where, $\mathrm{SP_{AST}}$ = ASTS set-point
$\mathrm{PGA_{SSE}}$ = PGA value at SSE
$\mathrm{C_f}$ = conversion factor
$\mathrm{A_f}$ = amplification factor
$\varepsilon_{\mathrm{hardware}}$ = ASTS hardware error

The amplification factor is defined as the ratio of the minimum floor response spectra (MinFRS) at the sensor location to the design ground response spectra (DGRS) of the free-field as depicted in Figure 11 and Equation (2). As shown, the Af varies from plant to plant. For example, the largest number of factors among the Korean nuclear power plant is around 1.8 when the 10 Hz low-pass filter is applied. In this figure YG, UN, KR, and WS stand for the NPP names. They are Younggwang, Unchin, Kori, and Wolseong respectively [18].

$$A_f = \frac{DGRS_{free\,field}}{MinFRS_{sensor\ location}} \qquad (2)$$

The ASTS hardware errors come from the digitalized hardware for the trip initiation logic and trip generation circuits. It can be broken down into three (3) elements; sensor (accelerometer) error, signal conditioning module error, and trip initiation logic error. The overall error is obtained by the sum of each error component as defined in Equation (3) since each error component is biased each other.

$$\varepsilon_{\mathrm{hardware}} = \varepsilon_{\mathrm{ACC}} + \varepsilon_{\mathrm{SCM}} + \varepsilon_{\mathrm{Bistable}} \qquad (3)$$

where, $\varepsilon_{\mathrm{hardware}}$ = ASTS hardware error
$\varepsilon_{\mathrm{ACC}}$ = accelerometer error
$\varepsilon_{\mathrm{bistable}}$ = bistable logic error

The error associated with the accelerometer is controllable through the periodic calibration. Normally, the maximum error of acceleration is controlled below 3% including all possible error sources. [19]

The error associated with the signal conditioning module (SCM) is somewhat difficult to control due to the frequency response of the low-pass filter. The filter error is varied by the filter type and order. The frequency response of the second order butterworth low-pass filter shows around 6% of overshoot.

Figure 12 shows the filter simulation result using real seismic waves that occurred in Fukuoka, Japan. The event occurred with a Mw of 7.6 in 2005. The filtered responses show an overshoot in positive polarity and an undershoot in negative polarity. The simulation result proves that the filter is the dominant error source of the ASTS.

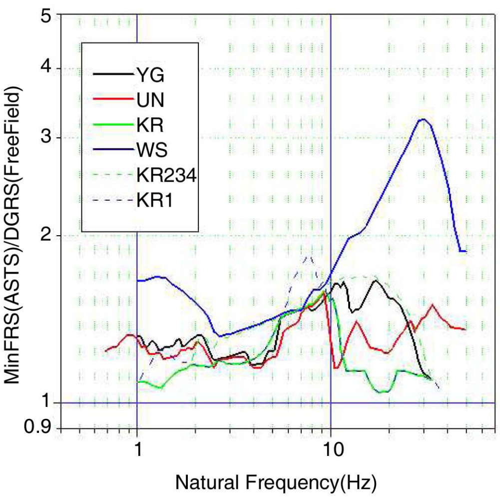


Fig. 11. Plots of Amplification Factors (at Reactor Basement)

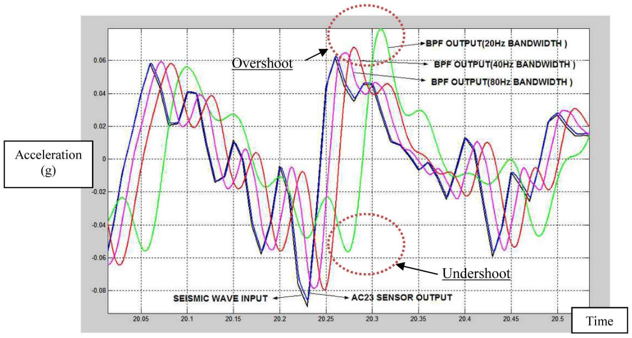


Fig. 12. Sensor with Filter response for X-axis Seismic Wave (Butterworth Filter ; Type= 8-order/BW, Cutoff Frequency= 10Hz, Bandwidth=20Hz).

4.3 Set- point Calculation

By adaptation of the requirements of RG1.60, the 30% of conversion margin is deducted from the PGA value of sensor location, so the conversion factor of 0.7 is applied. Figure 11 plots the amplification factors by the frequencies at the reactor building basement for Korean NPPs. In this case, the lowest amplification factor at 10 Hz is around 1.5.

Table 7 shows the calculation results of the ASTS trip set-point with the PGA at SSE of 0.2g. The reactor building basement that has 1.5 of amplification factor is projected. The calculated ASTS hardware error is 10%. The ASTS trip set-point is decided as 5.5% lower than the PGA at SSE. This value is the upper bound to put NPPs under safe conditions and to keep the SSC integrity.

Figure 13 expresses the actual ASTS set-point per NPP. It indicates that the applied trip set-point for an individual NPP is decided on below the upper bound depicted in Table 7 except Wolsong (WS) 1 and Ulchin (UN) 1&2. In this case, the amplification factor of WS 1 and UN 1&2 shown in Figure 11 affect to the setpoint calculation.

Table 7. Calculated ASTS Set-point (Upper Bound)

SP_{PGA}	PGA_{SSE}	C_f	A_f	ε_{ASTS}	$\frac{PAG_{SSE} - SP_{PGA}}{PAG_{SSE}}$
0.189g	0.2g	0.7	1.5	0.1	5.5%

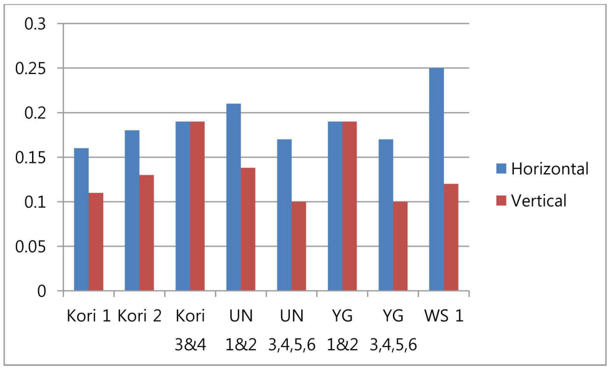


Fig. 13. Actual ASTS Set-point Per NPP

5. DESIGN VERIFICATION

To verify the design, the ASTS reliability is calculated using the RBD (reliability block diagram) method. Firstly, the sensor module is modeled then analyzed. Figures 14 and 15 respectively show the simplified RBD for the ASTS and sensor module respectively. Where, block 1 represents the reliability of sensor module and block 2 shows the overall reliability of ASTS.

Table 8 shows the applied data for the calculation. The failure distribution for the system is assumed to exponential since the equipment is composed of electronic devices. For the calculation, Bellfore Component Library is applied. The failure rate of rectifier is not accounted here because it is about 1. Equation (4) shows the reliability expression as having an exponential distribution.

$$R = e^{-\lambda \cdot t} \tag{4}$$

Where, λ=failure rate (failure/hour)
t=time (hour)

Table 9 shows the failure rate and reliability for sensor and module. Where the reliability of the sensor is calculated using the block diagram shown in Figure 16.

Table 10 shows the applied data for the calculation of ASTS cabinet. For this calculation, the data from the reference plant, Ulchin NPP 5&6 PLC, is applied as Table 11.

The calculation result using the above method is as shown in Table 11. Where, BS logic involves the components and modules from the analog input to input of two-out-four decision logic. The reason why we separate

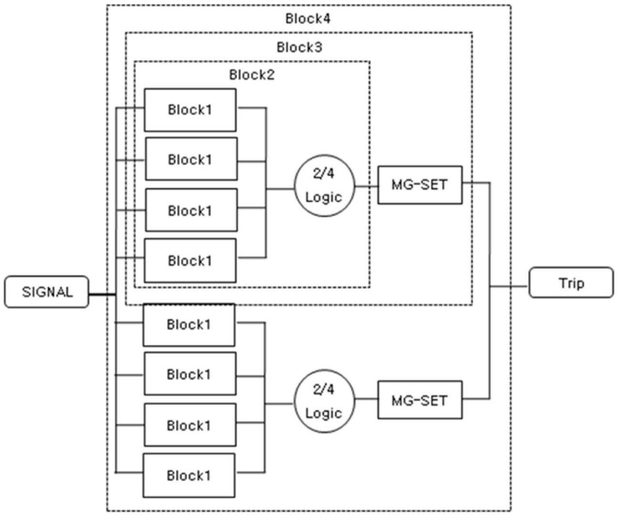


Fig. 14. Simplified RBD for AC-23 Accelerometer

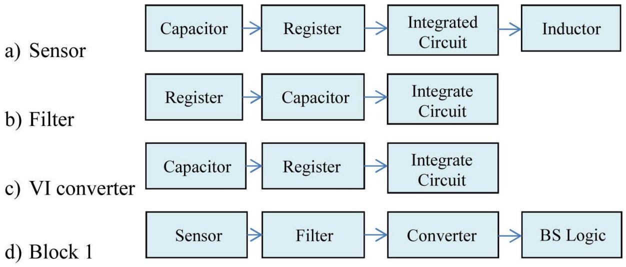


Fig. 15. Simplified RBD for Block 1

Table 8. Data for Failure Rate of Components (from Bellcore Com-Ponent Library)

Components	Failure rate (Bellcore)
Capacitor	1.881343E-09
Resistor, Fixed	2.606911E-09
IC, Analog/Linear	5.071121E-09
Inductor	8.323655E-10

Table 9. Failure Rate and Reliability for Sensor and Module

Components	Failure rate	Reliability	
		6 months	18 months
Sensor	1.039174E-08	0.999955109	0.999865332
Low-pass filter	9.559375E-09	0.999958704	0.999876118
VI Converter	9.559375E-09	0.999958704	0.999876118
Sensor Module	2.951049E-08	0.9998725228	0.9996176172

the decision logic and BS (bistable) logic is that single two-out-four decision logics of one channel is made by receiving two digital outputs from the adjacent channel.

The remaining items to be analyzed are breakers installed on the MG set control panel and reactor trip circuit breaker system (RTSS). The simplified RBD and the analysis results are shown in Figure 17 and Table 12 respectively.

The reliability analysis results for the ASTS using RBD are as shown in Table 13.

Figure 18 shows the calculated reliability by time. Because the reliability is inversely proportional to the time, the calibration period must be kept to maintain the target reliability. Through the reliability test, we validate that the ASTS can satisfy 0.95 of reliability without calibration

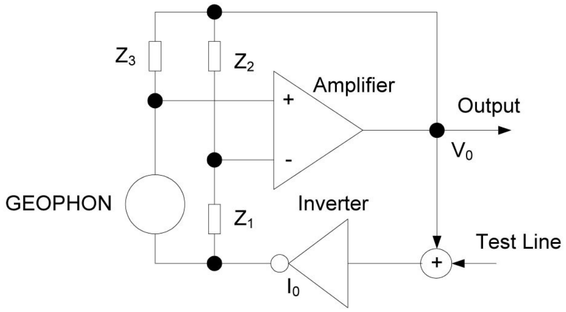


Fig. 16. Schematic Diagram for Seismic Sensor

Table 10. Data for Failure Rate of Components (from Reference Plant)

Components	Failure rate (Ulchin 5&6 PLC)
Analog input module	1.150000E-06
Processor module	3.010000E-06
Digital input/output module	6.300000E-07

Table 12. Failure Rate and Reliability for MG Set and RTSS

Components	Failure rate	Reliability	
		6 months	18 months
Block(MG-Set)	1.079900E-06/h	0.995345697	0.986101978
Relay	1.020000E-06/h		
Circuit Breaker	0.059200E-06/h		
Block(RTSS)	4.790000E-06	0.979519827	0.939809203
TCB	1.150000E-06		
UVTCR	3.010000E-06		
STCR	6.300000E-07		

Table 11. Failure Rate and Reliability for Bistable Logic

Components	Failure rate	Reliability	
		6 months	18 months
BS Logic	4.790000E-06	0.92975404086681	0.80371897856769

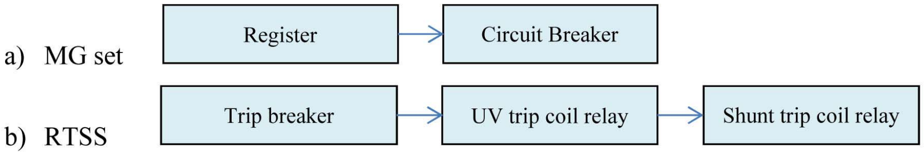


Fig. 17. Simplified RBD for Block 1

Table 13. Reliability Analysis Results for the ASTS using RBD

Reliability Block	Failure rate	Reliability	
		6 months	18 months
Block 1	$1-[1-R_{sensor}(t)* R_{filter}(t)* R_{converter}(t)* R_{BSLogic}(t)]^3$	0.99999125176663	0.99977800357934
Block 2	$[6R_{block1}^2(t) - 8R_{block1}^3(t) + 3R_{block1}^4(t)]*R_{2/4Logic}$	0.92975404086681	0.80371897857061
Block 3	$R_{block}^2(t)*R_{MG\text{-}SET}(t)$	0.92542668383955	0.79254887433766
ASTS	$1-[1-R_{block3}(t)]^2$	0.99443882051683	0.95696403046143

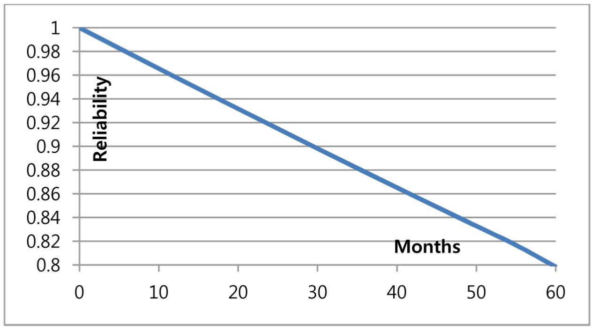


Fig. 18. Calculated Reliability Curve by Time

for 18 months. Then the functional test for the entire signal path is enough for 6 months as similar as criteria shown in ANSI/ANS 2.2 for seismic sensor.

6. CONCLUSION

This work shows the overall design stages of the ASTS using a systems engineering approach. It refers to the standard lifecycle process defined by ISO/IEC 15288 [20], but is modified to fit the operation of nuclear power plants.

By applying the systems engineering approach into the ASTS design, we can get a broad perspective of the design at the inception stage. The processes and activities to be performed are identified before the needs analysis stage. Through this approach, the schedule and investment can be optimized. It took around one year for the system design. It is quite short period of time to design the system considering it has quite new operational and functional concept.

ASTS is to provide proactive measure for the earthquake event. We expect that system unavailability will not be increased by introducing the ASTS for the indirect reactor trip function.

In Korea the operating NPPs have equipped the ASTS and now the design work is progressing for newly constructed NPPs. The characteristics of Korean ASTS design are:

- First kind of work to be performed by the systematic approach
- Digitalized and modular design
- Standardized design to fit the various reactor types
- Trip the reactor through diverse channel application

By designing the ASTS both fully digitalized and in a non-nuclear safe class, we can get some flexibility in the system design and implementations such as;

- Software discrimination algorithms can easily be applied for omitting the pseudo shock waves which is a likely incident
- System reliability can be increased due to configuring the major decision algorithm by software functional blocks

Throughout this work, the importance of filter design was identified in order to reduce the likelihood of a pseudo reactor trip. Yet the conventional accelerometer has a broader frequency range that is needed for application to NPPs. Therefore the external circuit which picks out the necessary frequency range as sharply as possible is essential. Normally higher order filters are applied but this introduces some level of uncertainty that adversely reduces the setpoint.

For performing the design verification quantitatively, specific methodologies to deal with setpoint and reliability have been developed. In order for this work, the RBD (reliability block diagram) method was applied. The results tell that the digitalized ASTS would not decrease both availability and reliability.

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