

Simulation Methods Development for a Plant Unit Master Control Logic Using Simulink in MATLAB

Changsun Yoon¹, Yeon-Chan Hong^{2*}

¹Electrical Instrumentation & Control Engineering Department, KEPCO-E&C

²Department of Electronics Engineering, Incheon National University

매트랩 시뮬링크를 이용한 플랜트 유닛마스터 제어로직 시뮬레이션 기법 개발

윤창선¹, 홍연찬^{2*}

¹한국전력기술(주) 전기계측기술그룹

²인천대학교 전자공학과

Abstract The simulators for a plant unit master control (UMC) developed by domestic or overseas researchers have been developed for operator-training purposes. UMC simulators normally constructed at the end of the plant construction, despite the UMC logics, should be simulated to pre-check many signal interfaces within the power generation systems. Because of the differences in construction schedule, it is difficult for logic designers or commissioning engineers to simulate the UMC logic during the design or commissioning stage. In this background, this paper proposes a simulation method that can be used easily by plant logic designers or operators in the MATLAB Simulink programming environment. The core of the UMC is realized with a unique simulation algorithm based on mathematical analysis and functional blocks combination. In addition, an integer-based configuration was proposed to realize the plant target value control for the equipment in the logic. With these simulation methods, functions, e.g., load distribution, high-low limitations, frequency compensation, etc. were simulated. The results showed that the plant UMC logic can be simulated in Simulink without a plant simulator. The various functions proposed in this paper can provide useful information about Simulink-based simulation design for plant logic designers or commissioning engineers during the power plant construction period.

요약 발전소 유닛마스터제어(UMC)용 시뮬레이터는 국내 및 해외에서 운전원 훈련 목적으로 개발되어 왔다. 일반적으로 UMC 시뮬레이터는 발전소 건설 마지막에 구축되는데, UMC 로직은 발전설비 내에 있는 많은 신호들 간의 간섭사항들을 사전에 확인하기 위해 시뮬레이션이 필수적으로 필요하지만 공정 일정 차이로 인하여 플랜트 로직 설계자나 시운전 엔지니어들이 UMC 로직을 시뮬레이션 하기는 쉽지 않다. 이러한 배경으로 본 논문에서는 발전소 로직 설계자와 운전원들이 매트랩에서 제공하는 시뮬링크 환경에서 손쉽게 구현할 수 있는 시뮬레이션 방법을 제안한다. UMC의 핵심기능이 수학적 분석과 기능 블록 조합이 기본으로 구성된 독특한 시뮬레이션 알고리즘을 통해 구현된다. 또한, 로직 내 설비 목표값 제어를 위해 정수기반 구성도가 제안된다. 이러한 시뮬레이션 기법들을 통해 부하 분배, 상-하한치 제한, 주파수 보상 등의 기능들이 시뮬링크 내에서 성공적으로 구현될 수 있음을 보이고, 결과적으로 우리는 UMC 로직을 플랜트 시뮬레이터 없이도 시뮬링크에서 구현할 수 있음을 보인다. 본 논문에서 제시한 다양한 시뮬레이션 기법들은 발전소 건설 기간 중 플랜트 로직 설계자 또는 시운전 엔지니어들을 위한 시뮬링크 기반의 시뮬레이션 설계 관련한 양질의 정보를 제공할 수 있을 것으로 사료된다.

Keywords : Load Demand, Plant Master Control, Simulator, Simulink, Unit Master Control

*Corresponding Author : Yeon-Chan Hong(Incheon National University)

Tel: +82-32-835-4769 email: ychong@inu.ac.kr

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1. Introduction

A unit master control (UMC) is the highest level control for setting the required load of a power plant. Set points for the UMC Control generate required signals for boilers and a turbine according to automatic dispatch system (ADS) or set point set by an operator[1]. The simulators for UMC developed by domestic or overseas researchers have been developed for operator-training purposes. Because UMC has many important signal interfaces with other power generation systems, it should necessarily be simulated before implementation. However, plant simulator is applied at the end of the plant construction, therefore it is hard for logic designers or commissioning engineers to simulate the UMC logic during design or commissioning stage. In this background, this paper proposes simulation methods that can be easily used by plant logic designers or commissioning engineers using Simulink programming environment in MATLAB. Previously, Simulink programming environment simulation for a balance of plant (BOP) has been introduced such as condensate pump's simulation using MATLAB[2], however, simulation methods for UMC realization in Simulink has not been developed yet. In this paper, simulation methods for functions, e.g., boilers and a turbine load distribution, high-low limitations, main steam pressure compensation, frequency compensation, etc. are developed to realize UMC logic in Simulink.

2. UMC Logic Realization Description

2.1 UMC Logic in General

Distributed control system (DCS) normally provides its own simulation function for the designated master control logic designed by an engineering company for the project[2]. Although the International Society of Automation (ISA) provides "Instrumentation Symbols and Identification"[3], however, no such information is provided for the Simulink application for a coal-fired

power plant's master control scheme.

In a general DCS, the system accumulates process information, e.g., temperature, pressure, level, flow, etc., for controlling and monitoring the process through transmitters, and with these information, the UMC finally controls the plant load in the DCS[4]. The core of the UMC is realized with unique simulation algorithm based on mathematical analysis and functional block combination. Simulation methods for UMC functions are introduced and they are simulated in Simulink programming environment.

2.2 Description of UMC

In the general plant industry, most master control logic is designed by binary logic and functional loops, which are based on analog signals[5]. For transferring or swapping analog values, a special functional block called a switching block is used for the function. With this block, signals can be changed or transferred according to the original design for the plant. For real-time control simulation, the elapsed time must be considered since the signal returns to the previous calculation, which is similar to a feedback control[6].

Three control modes: boiler-following mode, turbine-following mode and coordinated- control mode, are realized. Each mode is operated by the feedback value for its mode. In the boiler-following mode, for instance, the boiler load follows the turbine set point.

One of the main functions for the UMC is a frequency compensation. If the grid frequency changes, the set point for the turbine changes and the boiler follows the turbine load. The automatic frequency control (AFC) is possible in this mode. In the simulation, for instance, the boiler's set point is the turbine's output; therefore, the boiler's set point follows as the turbine set point varies. The mode selection can be set by transferring the manual switches in the simulation. The schematic for the master control concept is shown in Fig. 1.

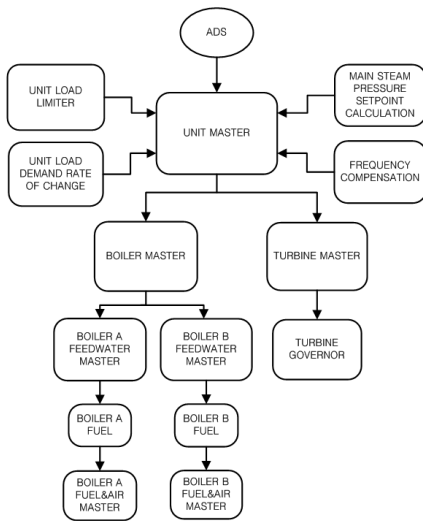


Fig. 1. Schematic for the master control concept

3. UMC Simulation methods development

3.1 Basic Functions for UMC

3.1.1 Plant Load Control

In the master control logic, the main function of the control logic controls the MW (megawatt) target for the main equipment. The logic calculates the target in accordance with other factors, e.g., grid condition, equipment capacity, operation modes, etc. The ramping rate[7] control is one of the important functions for controlling the power in terms of the boiler and turbine capacity. The ramping rate basically means how fast the value increases or decreases based on the elapsed time, by showing the value as a percentage, e.g., the

value per second or minute. The part of the integer-based master control logic with the ramping-rate function is shown in Fig. 2. The manufacturer for the equipment provides the information for the plant operation. The ramping rate provided by the supplier should be applied to the master control scheme for efficient operation.

It is also necessary to protect the equipment and the plant. The rate can be modified during the commissioning stage for tuning; however, the rate should basically be based on the manufacturer's design. The equipment's ramping rate is decided after considering all the relevant components in the equipment. Therefore, it is important to consider and fix the ramping rate at the beginning of the design stage.

3.1.2 Realization of F(X) Curve Function

An F(X) function is commonly used in a DCS, because it is very useful for transferring the signals for non-linear or unspecified input functions[8]. There are many applications with this function in plant-control systems. In most DCSs, the function is realized in accordance with the code, because the function is commonly used for process controls, such as valve opening, bias, range limitation, etc.

Several mathematical functions can be used for the F(X) function. Step functions, linear functions[9], exponential functions, etc., are commonly used. Although setting the F(X) in the DCS can be done without any mathematical calculation, to implement the

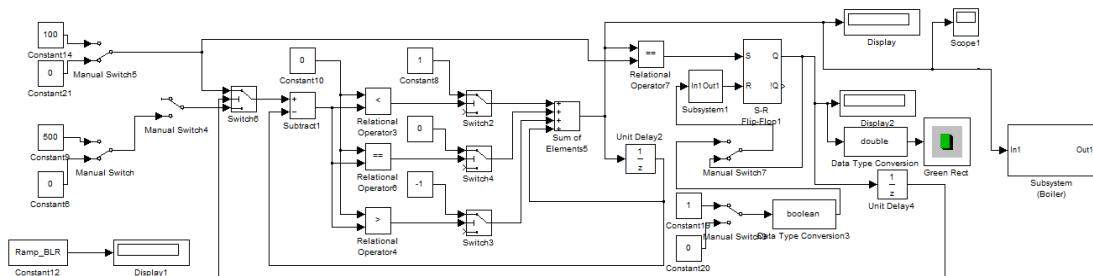


Fig. 2. Proposed configuration for a ramping rate function of UMC

identical function in Simulink, mathematical calculation is necessary to configure the functional blocks to generate identical output values.

3.2 Speed and Frequency in UMC

3.2.1 Droop Speed Control

Droop speed control is one of the speed-control modes for the prime mover[10], which leads the plant unit when generating electrical power connected to an electrical grid. In this mode, the generators can run in parallel with the grid by sharing the power rating. The frequency for the synchronous generator is shown in Equation (1).

$$F = \frac{P \times N}{120} \quad (1)$$

where

F =Frequency (in Hz),

P =Number of poles,

N =Speed of generator (in RPM).

The frequency (F) is directly proportion to the speed (N). In the electrical grid, if more than one synchronous generator is connected in parallel, the frequency does not vary because each generator's power is low compared to the grid. Because the generator's poles are different from each other, the frequency for the synchronous generators connected to the grid is the same while they run at various speeds.

When the generator is loaded to the base load, the speed of the prime mover is decreased. In this case, the speed reference for the prime mover is increased to increase the power. The speed for the prime mover is always fixed by the grid. To increase the power for the generator, the source of the power must be increased to make more power. The situation for the reverse is the same as the forward direction. The prime mover's actual speed allows its droop or decrease factor. The droop % for a Gas Turbine is given by Equation (2)[11].

$$\text{Droop}\% = \frac{\text{No load speed} - \text{Full load speed}}{\text{No load speed}}, \quad (2)$$

$$FSRN = (FSKRN2 \times (TNR - TNH)) + FSKRN1. \quad (3)$$

where

$FSRN$ =Fuel Stroke Reference (Fuel supplied to Gas Turbine) for droop mode,

TNR =Turbine Speed Reference,

TNH =Actual Turbine Speed,

$FSKRN2$ =Constant,

$FSKRN1$ =Constant.

The turbine speed is subordinated to the grid frequency, which is fixed for the network; the reference speed can be regarded as the turbine speed. During this operation, the power source is supplied for grid stability; the characteristic for the control philosophy is approximated by a linear function. The frequency-speed droop is the primary instantaneous parameter in control of an individual power plant's power output (kW)[6].

$$S = \frac{\Delta f_N}{f_N} \quad (4)$$

where

Δf_N is difference between no load frequency and rating rotation speed,

f_N is the grid frequency (rating rotation speed).

In Equation (4), S is the ratio of the frequency deviation when comparing the load versus the nominal frequency[12].

3.2.2. Speed Regulation

The UMC logic provides a frequency compensation function. Unbalanced properties produced in the system are shown as Equation (5)[13]:

$$\Delta P = \Delta G - \Delta L. \quad (5)$$

where

ΔG is the generation increment,

ΔL is the load increment.

If ΔF is the frequency variation in the system, F is

approximated as shown in Equation (6) below[13]:

$$\Delta F = (K_G + K_L) \Delta F - K \Delta F \quad (6)$$

where

K is the power-system constant and its unit is MW/0.1Hz[13].

K_G is the power-system constant for governor (generation increment),

K_L is the power-system constant for power load (load increment).

3.2.3 Frequency Compensation in the UMC

As the grid frequency changes when the droop control is applied to the turbine, the compensation for the boilers and turbine load demand must be applied to the load calculation. The UMC logic has the compensation function. In frequency-compensation mode, the function calculates the compensation value with the frequency error, which is transferred from the turbine, and the signal passes through the limitation function. The final compensation value is added to the main load demands for the boilers and a turbine. As a result, the fuel consumption rate is changed as per the compensation values in accordance with the frequency error.

3.3 Realization of Functions and Simulations in UMC

3.3.1 Realization of High-Low Limitations

To realize limitation function for the frequency-error compensation, two different types of linear-function groups are applied to the simulation. The designed function is operated as a high- or low-path filter according to the limit values. The overall range between the high limitation and low limitation for the frequency-compensation function is gradually increased and, after a certain point, is gradually decreased because the high limitations hold for the maximum load operation.

A combination of a few linear functions can demonstrate the range-limitation function. It is

composed of several linear functions to match F1(X), F2(X)[14] for the limitation of the master control logic, as shown in Table 1[14] and Fig. 3.

To realize the graphs for F1(X) and F2(X) in Simulink, each range of the function is approximated as a mathematical function. Assume that each of the functions can be approximated as a linear function, forming the Equation (7):

$$y = \frac{dy}{dx} x + b. \quad (7)$$

Table 1. F1(X) and F2(X) table for high-low limitations

X	F1(X)	F2(X)
520	0	0
640	-40	40
800	-100	100
1000	-100	20
1050	-100	5

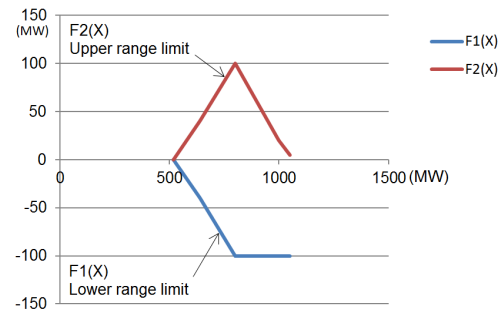


Fig. 3. F1(X) and F2(X) graph for high-low limitations

The derivative values for the functions are achieved by calculating dy/dx with the information in Table 2 and Table 3.

Once dy/dx is calculated, y-intercept “ b ” is calculated by inserting zero into x . The other data for the F1(X) functionalization is shown in Table 2 and the data for the F2(X) functionalization is shown in Table 3.

The functions approximated in Table 2 and Table 3 can be visualized in MATLAB by programming in the command window. The screenshot for this work is shown in Fig. 4. To verify the designed logic, a customized source is applied to the logic.

Table 2. Data for the F1(X) functionalization

	$x_1(a)$		$x_1(b)$		$x_1(c)$		$x_1(d)$		$x_1(e)$		$x_1(f)$
x_1	0	0-520	520	520-640	640	640-800	800	800-1000	1000	1000-1050	1050
	$y_1(a)$		$y_1(b)$		$y_1(c)$		$y_1(d)$		$y_1(e)$		$y_1(f)$
y_1	0	0	0		-40		-100		-100		-100
	$x(b)-x(a)$		$x(c)-x(b)$		$x(d)-x(c)$		$x(e)-x(d)$		$x(f)-x(e)$		
dx_1		520		120		160		200		50	
	$y(b)-y(a)$		$y(c)-y(b)$		$y(d)-y(c)$		$y(e)-y(d)$		$y(f)-y(e)$		
dy_1		0		-40		-60		0		0	
dx_1/dy_1		0		-0.33333		-0.375		0		0	
	$y_1(b)-(x_1(c)-x_1(b)) \cdot x_1(b)$				ditto		ditto		ditto		ditto
β_1				173.3333		200		-100		-100	

Table 3. Data for the F2(X) functionalization

	$x_2(a)$		$x_2(b)$		$x_2(c)$		$x_2(d)$		$x_2(e)$		$x_2(f)$
x_2	0	0-520	520	520-640	640	640-800	800	800-1000	1000	1000-1050	1050
	$y_2(a)$		$y_2(b)$		$y_2(c)$		$y_2(d)$		$y_2(e)$		$y_2(f)$
y_2	0	0	0		40		100		20		5
	$x(b)-x(a)$		$x(c)-x(b)$		$x(d)-x(c)$		$x(e)-x(d)$		$x(f)-x(e)$		
dx_2		520		120		160		200		50	
	$y(b)-y(a)$		$y(c)-y(b)$		$y(d)-y(c)$		$y(e)-y(d)$		$y(f)-y(e)$		
dy_2		0		40		60		-80		-15	
dx_2/dy_2		0		0.33333		0.375		-0.4		-0.3	
	$y(b)-(x(c)-x(b)) \cdot x(b)$				ditto		ditto		ditto		ditto
β_2				-173.3333		-200		420		320	

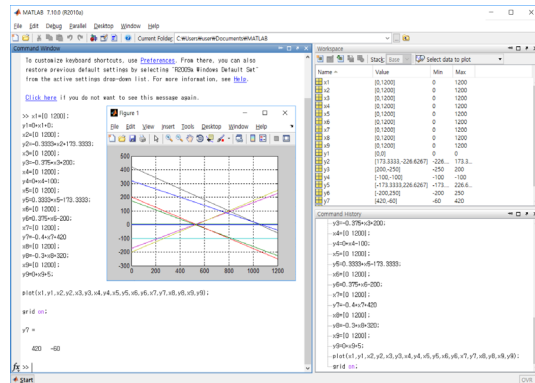


Fig. 4. Screenshot of the function-graph generation work

It is demonstrated that the response matches, as per the designated F1(X) and F2(X) values, which are designated in accordance with the previously calculated linear function. The configuration for the F1(X) and F2(X) realization is shown in Fig. 5, and the result for the configuration is shown in Fig. 6.

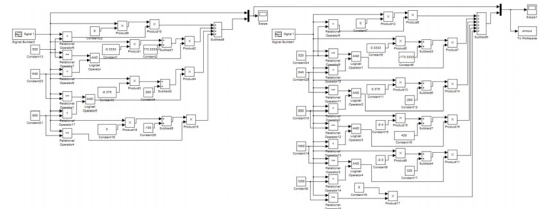


Fig. 5. Proposed configuration for F1(X) and F2(X) realization

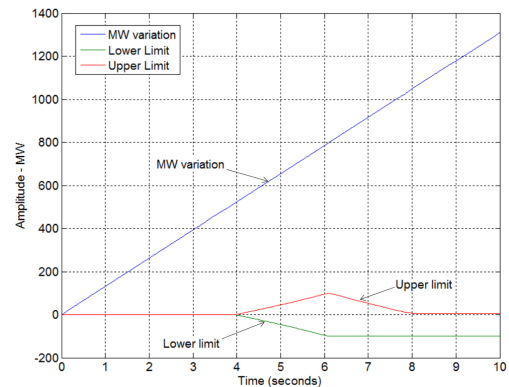


Fig. 6. Result for the configuration of F1(X) and F2(X) realization

3.3.2 Main Steam-Pressure Compensation

The lower the pressure, the lower the impact of the main steam pressure in terms of the frequency compensation; the compensation coefficient can be applied as the main steam pressure varies.

The main steam pressure versus the compensation coefficient is given in Table 4[14], according to the UMC. The variation for the coefficient is demonstrated in Fig. 7.

Table 4. Main steam-pressure compensation coefficient

X	F3(X)
0	0.8
280	1

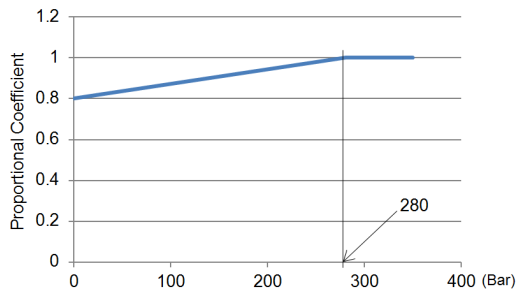


Fig. 7. F3(X) graph for the main steam-pressure compensation

The main steam-pressure compensation-coefficient calculation can be configured as shown in Fig. 8 and the function F3(X) is approximated as shown in Fig. 9.

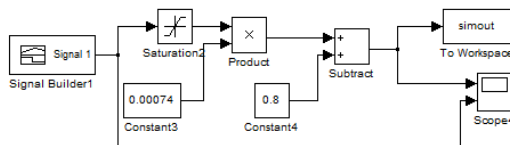


Fig. 8. Proposed configuration for the main steam-pressure compensation

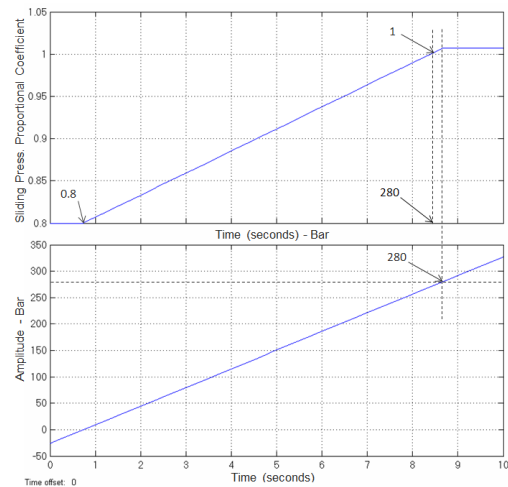


Fig. 9. Simulation result for the F3(X) function

3.3.3 MW Calculation for the Frequency

To compensate the MW, the compensation value is calculated by the percent value of the frequency error given in Table 5[14].

Table 5. F4(X) table for the frequency error compensation

X	F4(X)
-15	100
-10	100
-1.2	0
1.2	0
10	-100
15	-100

In Table 5, the X value is the percentage value and the value for F4(X) is the MW output. If the frequency-error percentage is between -1.2 and 1.2, the output will be zero. If the percentage's absolute value is between 1.2 and 10, the output will comply with the function shown in Fig. 10. The graph for F4(X) is shown in Fig. 10 and the proposed configuration for the MW-compensation function is shown in Fig. 11.

The signal given to the signal builder is to demonstrate that F4(X) calculates the MW output value according to Fig. 11. For the given input, the output value complies with F4(X), as shown in Fig. 12.

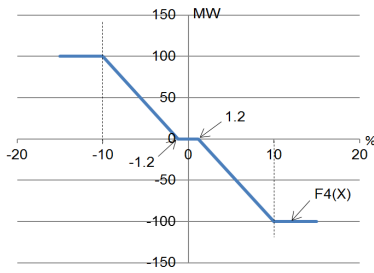


Fig. 10. MW for the compensation value

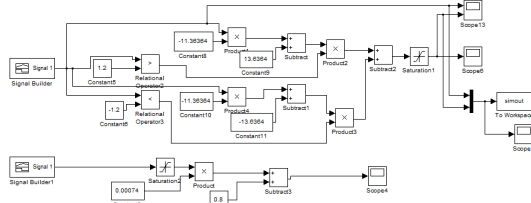


Fig. 11. Proposed configuration for the MW compensation function

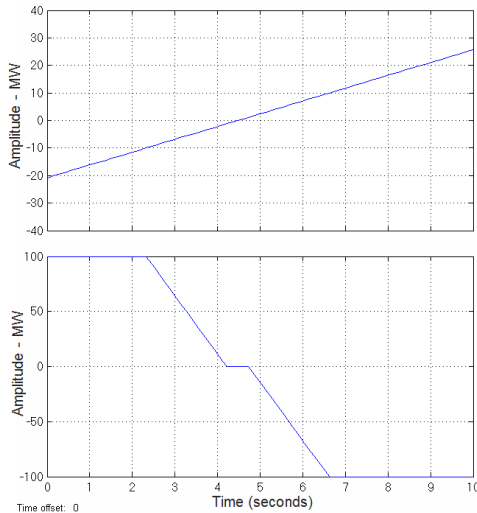


Fig. 12. Simulation result for the MW compensation value

3.3.4 Simulation for the Frequency Compensation Operation

With the information above, a simulation for the frequency compensation is configured. Although, manual operation is used to set the MW power for a small-capacity turbine operation on the grid[15], it is considered that large-capacity turbine operations

contribute to high grid stability. In an arbitrary situation where a frequency error is generated between the turbine and the grid, the simulation demonstrates that the calculated value is generated accordingly.

For the calculation, the frequency error value is referred from the turbine and the grid. The MW value is calculated through the $F4(X)$ filter. The calculated MW value is multiplied by the value calculated from $F3(X)$ according to the main steam pressure. The final compensation value will be achieved with the high-low path filter, which was already designed in Section 3.3.1. The generated compensation value directly affects the unit load as shown; therefore, the final set point for the load is changed for compensation. Actual configuration of load calculation for a DCS system is shown in Fig. 13[8].

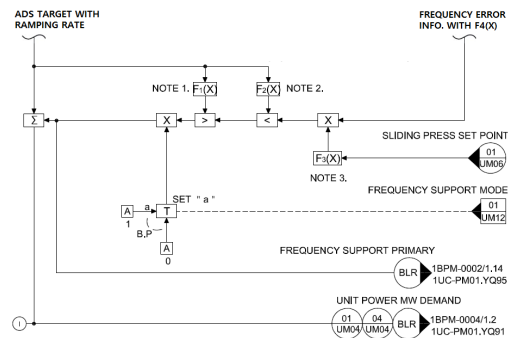


Fig. 13. Actual configuration of load calculation

Frequency calculation is related to “droop speed control”, which is already described in Section 3.2.1. Hypothetical trends of frequency response, RPM, inlet guide vane position and actual load are shown in Fig. 14 and Fig. 15.

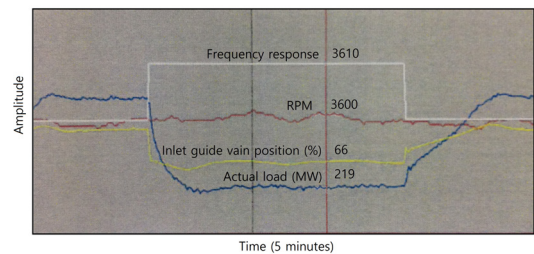


Fig. 14. Trends of frequency response (case 1)

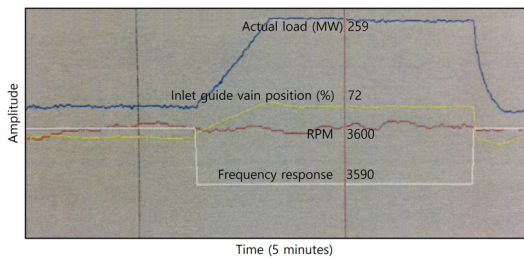


Fig. 15. Trends of frequency response (case 2)

Inlet guide vane is the main equipment to control the turbine speed; the rate of the inlet guide vane is related to turbine speed control. In Fig. 14, the relations for the inlet guide vane position 66% and actual load 219 MW are shown in accordance with the frequency response 3610 rpm. Trends for the reverse frequency response are shown in Fig. 15.

To simulate this concept, proposed frequency compensation configuration is designed as shown in Fig. 16. In the figure, assume that the grid frequency is 60 Hz and the turbine frequency is 58, to demonstrate the compensation. The frequency error between the grid and the turbine is -2Hz ; therefore, the frequency error is -3.3333% . The percent value goes into the MW compensation blocks for $F4(X)$. The calculated MW-compensation value is multiplied by the

main steam-pressure compensation value with $F3(X)$. The MW value 24.25 for compensation is obtained. The value goes through the limitation filter, in which the limit values are calculated: 20 for the high limitation and -100 for the low limitation. The calculated 24.25 exceeds 20, so 4.25 is subtracted from 24.25; therefore, 20MW is the final compensation value.

3.3.5 UMC simulation

With the information in Chapter 3, the UMC simulation is developed as shown in Fig. 17. In the actual plant, all related systems in a power plant must be ready to operate the UMC, therefore, we applied related systems operation conditions, e.g., BOP system, condensate system, feedwater system, etc. to simulate the UMC. Virtual models for two boilers and one turbine are designed to simulate the coal-fired power-plant unit capacity of 1,000 MW fossil power plant (combination of two boilers and one turbine) system.

The responses for the boilers and a turbine are used as a reference of the unit load distribution for the load control concept shown in Section 3.1.1. Control concept can be selected as per the UMC control mode.

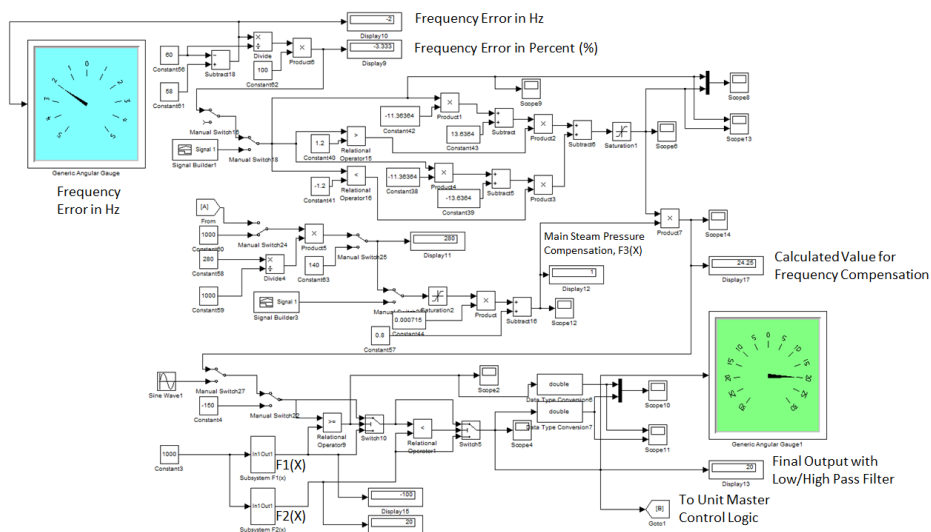


Fig. 16. Proposed configuration for the frequency compensation operation

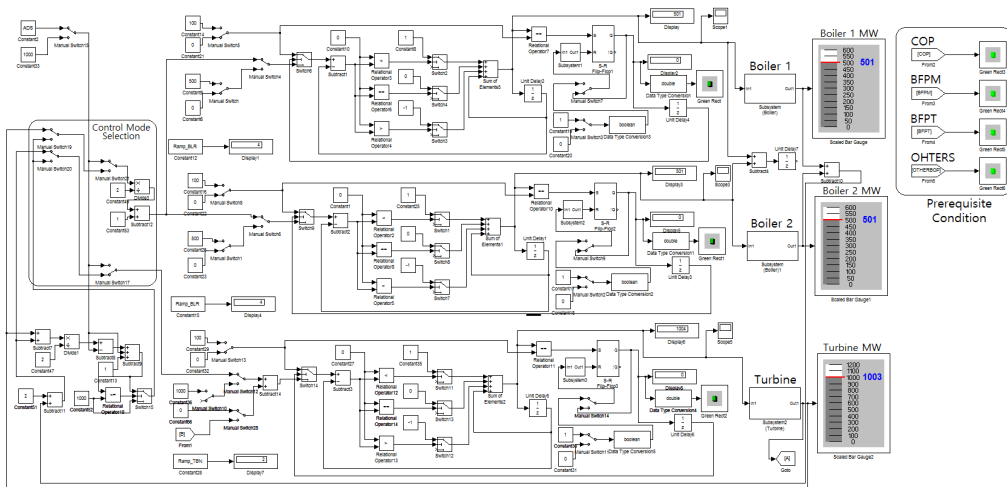


Fig. 17. Proposed configuration for UMC logic simulation

The variation for the output for the units is shown in the graphic. It is demonstrated that the proposed simulation methods can simulate the core of UMC logics in Simulink environment. The proposed configuration for UMC logic simulation is shown in Fig. 17.

4. Conclusion

Despite the importance of UMC in a power plant, simulation methods in Simulink environment have not been developed. For this reason, it is hard for logic designers or commissioning engineers to simulate the UMC logic during design or commissioning stage before the simulator is constructed. This paper proposed simulation methods that can be easily used by plant designers or operators using Simulink in MATLAB. We demonstrated how the plant master-control logic could be simulated in Simulink. The logics were re-interpreted for UMC implementation in Simulink. Especially, to realize the master-control logic for the power plant, an integer-based configuration was proposed to comply with the original concept for the plant master-control scheme. With these works, we demonstrated that the

proposed simulation methods could simulate power plant's UMC core logic using Simulink in MATLAB. It is considered that the proposed simulation methods can be an effective method for UMC Simulation in the plant industry in which the major concerns are logic development or commissioning engineer's practice, rather than actual plant operation.

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Yeon-Chan Hong

[Regular member]



- Feb. 1985 : Seoul National Univ., Electronics Engineering, MS
- Feb. 1989 : Seoul National Univ., Electronics Engineering, PhD
- Mar. 1990 ~ Feb. 1992 : Soon Chun Hyang Univ., Dept. of Electronics Engineering, Full-time lecturer

- Mar. 1992 ~ current : Incheon National Univ., Dept. of Electronics Engineering, Professor

<Research Interests>

Control and Instrumentation, RFID, Home Networking

Changsun Yoon

[Regular member]



- Feb. 2012 : Korea Univ., Electronics and Computer Engineering, MS
- Feb. 2017 : Incheon National Univ., Electronics Engineering, PhD
- Mar. 2004 ~ current : KEPCO -E&C., Elec., Instrumentation and Control Engineering Dept.
Senior Manager / Specialist

<Research Interests>

Control and Instrumentation, RFID, Power Plant Simulation