Application of Dynamic Model for Steam Turbine and its Parameter Estimation in a Fossil Fired Power Plant

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Abstract

The 500 MW rated steam turbine model in coal fired power plant is developed to be used for validation and verification of controller rather than for the education of operator. The valve, steam turbine, reheater and generator are modeled and integrated into the simulator. And the data from the plant heat balance diagram are used for estimation of the model parameters together with actual operating data. It is found that the outputs of model such as pressure, temperature and speed are similar to the operating ones. So, it is expected that the developed model will play a very big role in controller development.

Keywords: Steam turbine, model, parameter estimation, control

I. INTRODUCTION

Presently, there are many demands for upgrade and change of old control system for steam turbine in Korea since they have been running for a long time. But it is very difficult to start up power plant without any fault in developed control system. Therefore, the model within simulator needs to be developed and be used for the new control system test by performing real-time simulations before application to actual plant. In this paper, the development of mathematical models is first introduced and estimation method of model parameters is shown to analyze response of control valve, steam turbine, reheater and generator based on the energy balance. Then the values of parameters are decided by use of the measured or design data and the control logic for speed controller is developed. Finally, the simulation test is performed in the field before speeding up the turbine actually.

II. SYSTEM DESCRIPTION OF STEAM TURBINE

A steam turbine of a 500 MW thermal power plant is considered for the modeling approach. Fig. 1 shows that a high pressure (HP) turbine is a unity with an intermediate pressure (IP) turbine. And they are directly coupled with two low pressure (LP) turbine. In addition, the system includes reheater, and the related components.

The following valves regulate the flow of steam in boiler superheater to each turbine as follows.

- Main Stop Valve (MSV, 2 ea): To shut off steam flow to HP turbine
- Control Valve (CV, 4 ea): To regulate steam flow to high pressure turbine
- Reheat Stop Valve (RSV, 2 ea): To shut off steam flow to IP turbine
- Intercept Valve (IV, 2 ea): To regulate steam flow to IP turbine

The IVs are widely opened in normal operation and the CVs are controlled by the variation of speed and electric power. The steam pressure from superheater is the input to the HP turbine. The entered steam expands in the HP turbine and is discharged into the reheater. The cold steam passes through reheater to IP turbine, LP turbine and finally goes to the condenser.

The temperature and pressure of steam at the inlet of HP turbine are 538 °C and 169 kg/cm^2 respectively which comes from boiler superheater originated from drum. And The temperature and pressure of steam at the inlet of IP turbine are 538 °C and 36 kg/cm^2 which comes from HP turbine exhaust.

III. MODEL DEVELOPMENT AND PARAMETER DECISION

We choose flow rate, pressure and enthalpy as the major variables in thermal-hydraulic modeling of each component, which are calculated from the mass, energy and momentum equations. The other thermodynamic variables are computed from the equation of state. In a power plant including many thermal-hydraulic components such as valves, turbines and heaters, the dynamic variables of each component are strongly coupled with those of the connected components. Therefore, the governing equations for all the components should be solved simultaneously. Specially, the pressures at the point of inlet and outlet of every thermal-hydraulic component are determined from the operation condition, which is derived by combination of the mass and momentum equations for all the other components. The measured data from actually running turbine and the design data of turbine are used for calculation of turbine energy, loss factor, inertia and so on.

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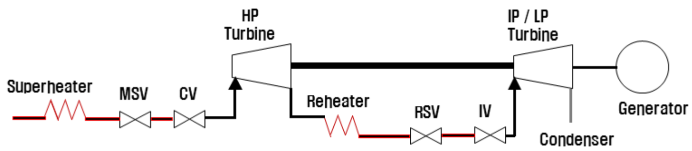

Fig. 1. Turbine configuration.

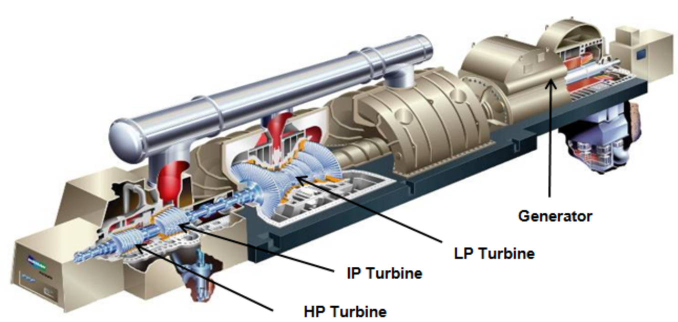

Fig. 2. 500 MW steam turbine at thermal power plant.

A. Dynamic Model Development

The components of dynamic model are steam turbine, main stop valves, control valves, reheater and generator. And such process variables as steam pressure, steam temperature, steam flow, turbine speed and generator output should be calculated from the thermodynamic equations in dynamic model according to the change of valve position. Every equation for modelling is depicted precisely in the reference [1]. The admittance of steam turbine and valves are calculated by the measured operating data.

The steam turbine model can be developed by taking following principles into consideration. The high-pressure steam enters the turbine through a stage nozzle designed to increase its velocity [2]. The pressure drop produced at the inlet nozzle of the turbine limits the mass flow through the turbine [2]. A relationship between mass flow and the pressure drop across the HP turbine was developed by Stodola in 1927 [2]. The relationship was later modified to include the effect of inlet temperature [2].

The valve model can be developed by taking following principles into consideration. A valve is used to control the steam flow by restricting the cross-sectional area of pipe. The relationship between position and steam flow can be evaluated from the operating data of the target plant. According to the thermodynamic principle, no change in enthalpy is assumed for the throttling process across a valve.

The reheater model can be developed by taking following principles into consideration. A reheater is located between the HP turbine and the IP turbines, as shown in Fig. 1. It gives heat flux into cold reheat steam leaving HP turbine in order to increase the degree of superheat. For mass, energy and momentum inside the reheater, 3 conservation equations of energy, mass and momentum can be taken into consideration.

The generator model can be developed by taking following principles into consideration. A generator produces electricity from the kinetic energy of turbine rotor with the generator connected to the power system. When it is off the grid, however, the thermal power of turbine increases the speed of turbine-generator until it balances with the mechanical loss. Fig. 3 is an examples of developed model together with Fig. 4.

Fig. 3 includes the process variables of reheater such as flow, pressure, enthalpy, temperature, specific volume and etc.

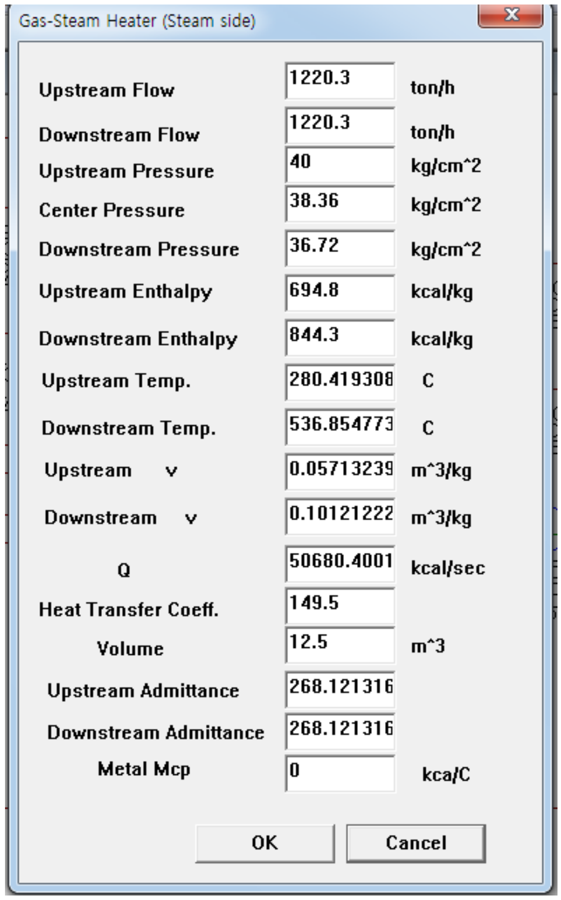

Fig. 3. Reheater model.

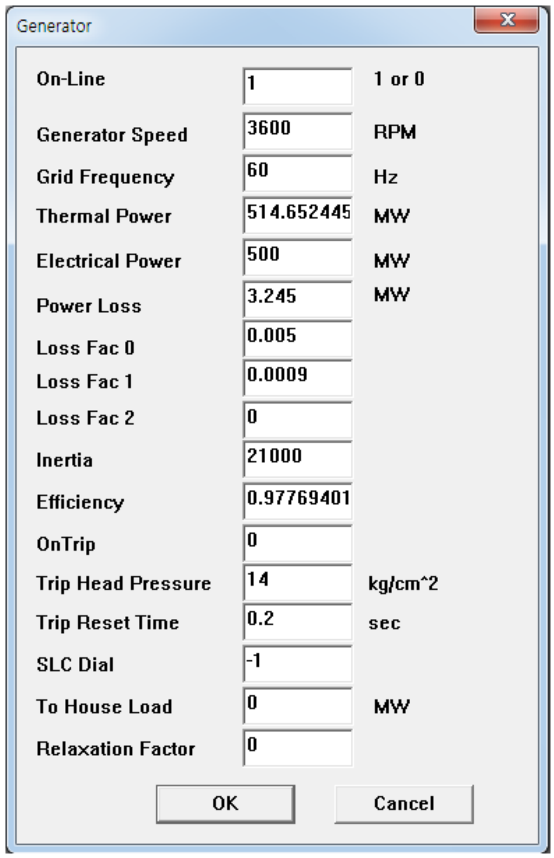

Fig. 4. Speed model.

Table 1. Data for turbine model

Load (%)	75				100			
Steam condition	P (kg/cm²)	T (°C)	H (kcal/kg)	F(t/h)	P	T	H	F
After SH	201.1	537.8	802.8	1088.1	247.1	537.8	789.8	1512.8
Before HP	195.1	-	802.8	1088.1	239.7	-	789.8	1512.8
Packing	-	-	775.4	14.5	-	-	767.8	20.2
1st extraction	49.0	-	725.8	72.5	66.4	-	719.1	116.6
Before RH	29.9	-	700.9	897.4	40.4	-	694.8	1216.9
After RH	27.17	537.8	846.5	900.2	36.72	537.8	844.3	1220.3
Before IP	26.60	-	846.5	900.2	36.00	-	844.3	1220.3
1st extraction	11.91	-	788.0	32.7	16.06	-	786.3	47.8
to FP	6.49	-	749.8	51.3	8.58	-	747.5	85.0
Before LP	6.30	-	749.8	800.3	8.30	-	747.5	1063.5
1st extraction	3.61	-	716.9	56.2	4.74	-	714.6	81.4
Condenser	0.052	-	560.0	661.8	0.052	-	550.7	857.6

Fig. 4 includes the process variables of turbine and generator such as generator speed, grid frequency, thermal power, electric power, power loss, loss factor, inertia and etc.

B. Parameter Decision

There are many parameters to be determined by use of the data from the heat balance diagram and operating data such as steam pressure, steam temperature, condenser pressure and condenser temperature. The valve characteristic curve is another important element for steam flow which can be obtained from operating data too. The procedure of parameter estimation is shown in Fig. 5 and the design data to use for turbine model is shown in table 1. The natural speed decay curve, as shown in Fig. 6, for turbine speed is used to calculate the inertia, friction, windage loss and the position of CVs at no load and rated speed. In Fig. 6, the vertical axis represents the decayed speed the 100% of which is 3,600 rpm and horizontal axes represents the elapsed time the duration of which is 3,186 seconds.

IV. SPEED CONTROL ALGORITHM

The speed control algorithm in the new control system is very simple as shown in Fig. 8. The ramp block outputs ramp at a certain rate depending on selected rate. Speed Set and Speed Ref Rate are selected by operator. Speed Set means a target speed and its pre-defined values are 360, 200, 480, 3,600 rpm. Speed Ref rate is the acceleration ratio of turbine speed according to the passed time and its pre-defined values are 0, 120, 180, and 360 rpm/min. The "Hold" means the acceleration rate is 0 rpm/min. Speed Ref is automatically calculated by the function of ramp block. The parameters and variables used in this section are illustrated as followings.

K_p : Proportional Gain
ΔF : Speed Error
CVR : Control Valve Reference
IVR : Intercept Valve Reference

A. CV Control

In Fig. 8, $K_p \cdot \Delta F$ is decided by a speed error(ΔF) and gain of proportional controller. $K_p \cdot \Delta F$ increases when an actual turbine speed is lower than speed ref and CVs are more opened by increased CVR then the actual turbine speed increased. CVR is calculated by adding $K_p \cdot \Delta F$ to load reference and controls all the

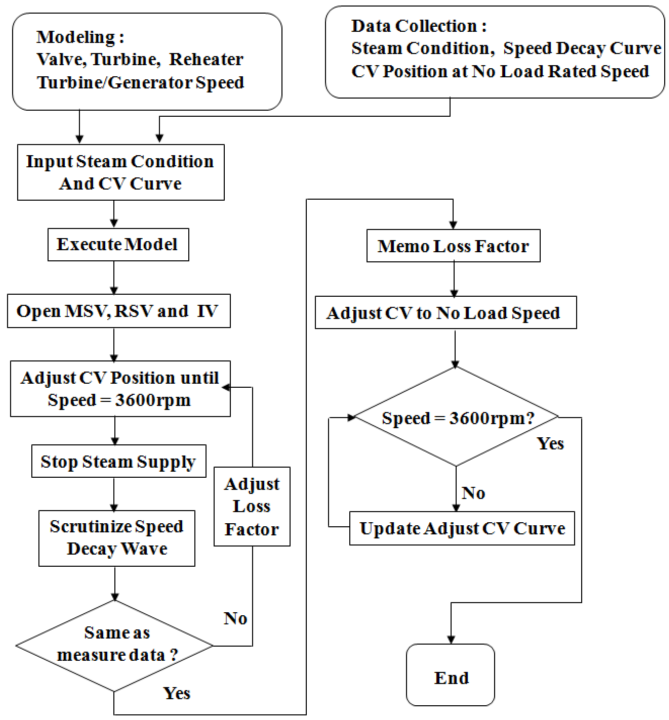

Fig. 5. Procedure of parameter estimation.

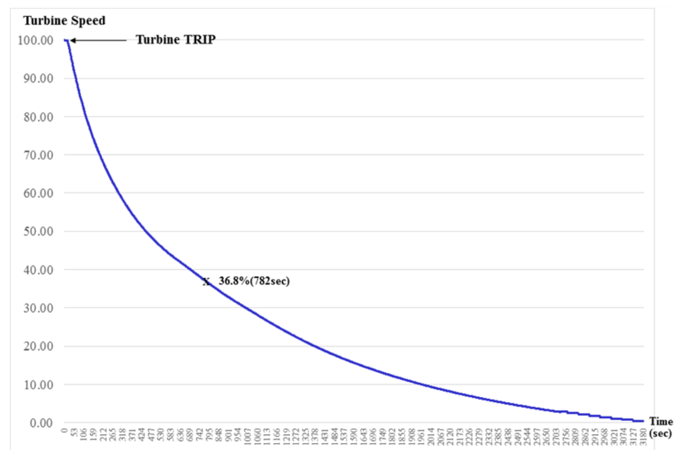

Fig. 6. Natural speed decay.

CVs during speed up and loading as following equation in which common value of K_p is 20

$$CVR(\%) = K_p \cdot \Delta F + Load\ \ Reference \tag{1}$$

At rated operation condition, as normally Load Ref. is 100%, CVR is as follows

$$CVR(\%) = 20 \cdot \Delta F + 100 \tag{2}$$

This means, the CVs start to close at above 100% speed and go to 0% position at 105% speed.

B. IV Control

In Fig. 9, the IVs control the turbine speed according to the following relationship. The IVs control and prevent overspeed especially with the bias 100% plus the factor of Load Ref. The relationship between CVR and IVR is as follows.

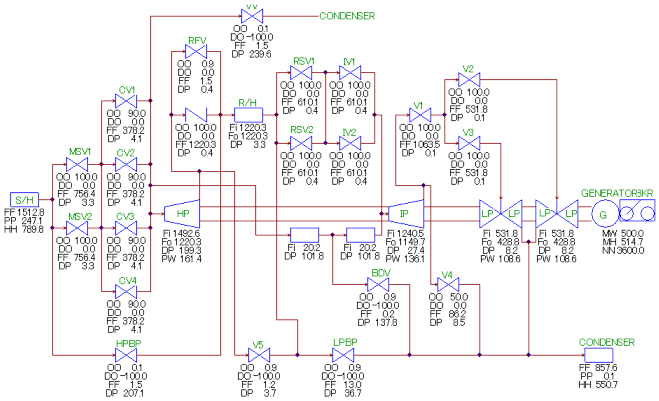

Fig. 7. Steam turbine model after parameter decision.

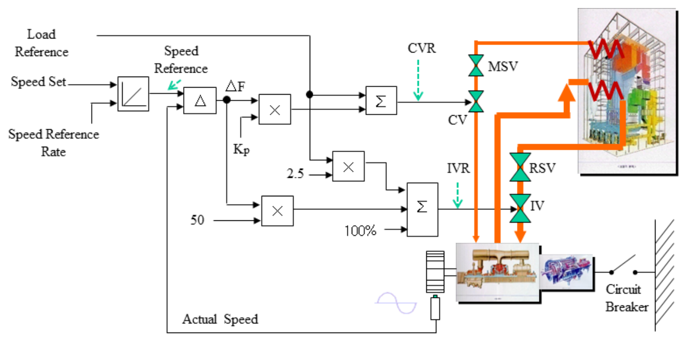

Fig. 8. Overview of speed control algorithm.

$$\mathrm{IVR}(\%) = Load\ \ Reference \times 2.5 + 50 \times \Delta F + 100 \tag{3}$$

This means that IV needs to be opened fully, though the CV is at its 0 position at the initial start-up, for the CV to control turbine speed from standstill to full speed. The bias 100% enables the IV to pass all of the steam which come from CV through HP turbine and Reheater.

At rated operation condition, as normally Load Ref. is 100%, IVR is as follows

$$\mathrm{IVR}(\%) = 250 + 50 \times \Delta F + 100 \tag{4}$$

Therefore, the IVs start to close at 105% speed and go to 0% position at 107% speed. The graphical description between IVs and CVs shown in Fig. 9.

V. SIMULATION

The simulation is performed when the installation of the new control system is completed. Every control signal can be confirmed in its good state in this method. The models are integrated into turbine simulator in Fig. 10.

On the basis of the configuration shown in Fig. 10, all of the operation procedure including the following important items can be tested.

- Reset and Speed Up
- Speed Matching and Synchronization
- Admission Mode Selection
- Increase and Decrease of Generator Load
- Valve Closing Test
- Emergency Overspeed Trip Test
- Load Rejection

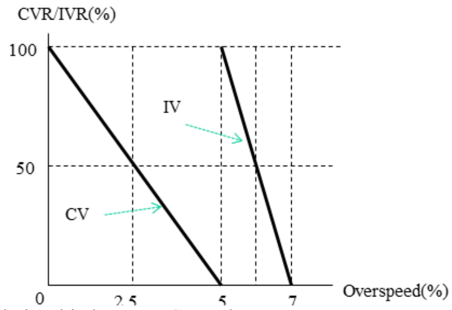

Fig. 9. The relationship between CV and IV.

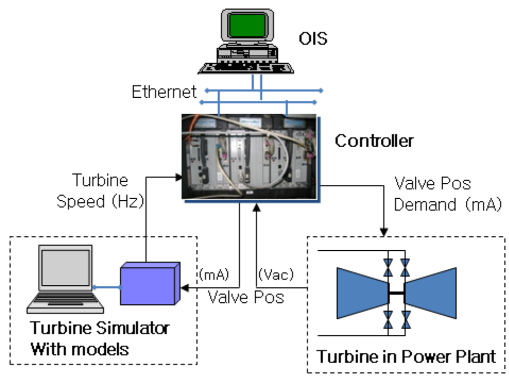

Fig. 10. Pre-startup simulation.

A. Method

In Fig. 10, when the operator selects command for speed up on operator interface station displayed in Fig. 11, this command enters into the controller and the speed target of the controller increases.

Accordingly, the valve position demands increase and the electrical signals are injected into the turbine fields. In this simulation step, since all of the instruments in the field can be operable, every valve such as control valves and intercept valves can be controlled according to the command followed by controller output. So, the controller can detect the valve positions and send them into the turbine simulator. Therefore, the model existing in the simulator calculates turbine speed and feed backs to the controller.

In this way, turbine speed can be up or down and every condition of field instruments and drivers can be checked prior to the actual operation. If any fault or out of order with the field instrument are found during pre-startup simulation, every malfunction can be repaired before actual operation. This is very helpful to the management of power plant. Fig. 12 shows the procedures for pre startup simulation test for only speed up.

The simulation test is to test the speed control functions of controller prior to start up. This simulation test was accomplished after the speed control system was installed in actual power plant.

B. Result

The test results of pre startup simulation for 20 minutes are displayed on Fig. 13, which shows the simulation result when the operator selects speed targets as 200, 800, 3,600 rpm on the operator interface station. The IVs go to 100% position and CVs start to open to speed up the turbine after MSV2 and MSV1 are open when the operator selects 200 rpm of speed set with a speed rate. Turbine speed control is in its good state from standstill to rated speed with the positions of CVs at 5-6% [3].

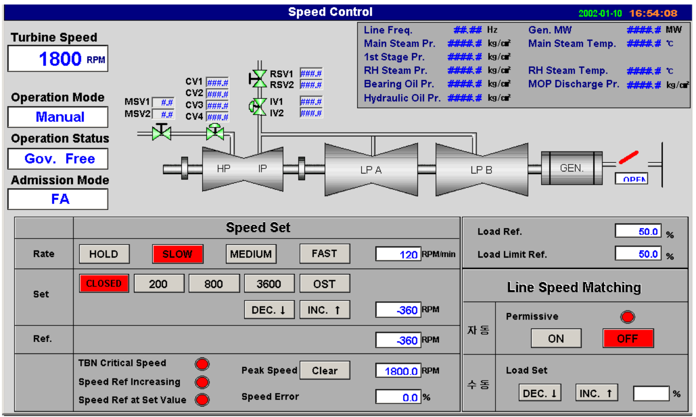

Fig. 11. Operator interface station.

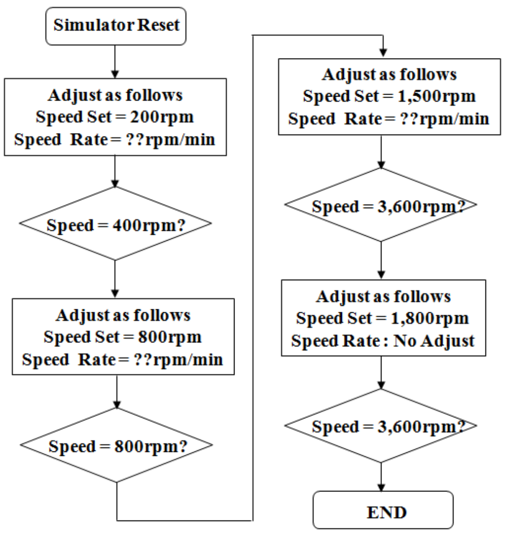

Fig. 12. Procedure of simulation.

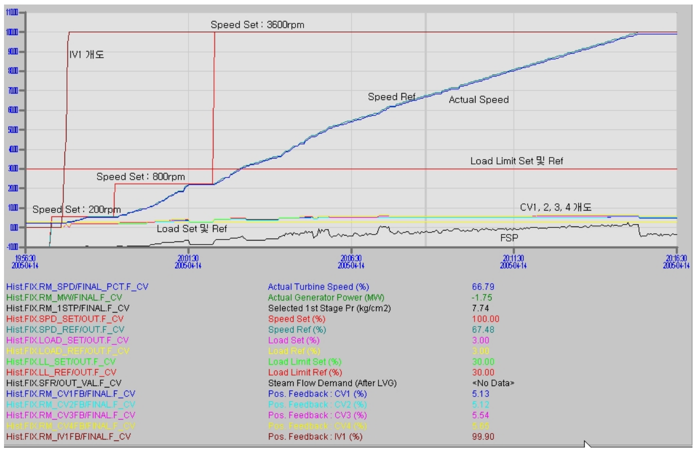

Fig. 13. The pre-startup simulation result.

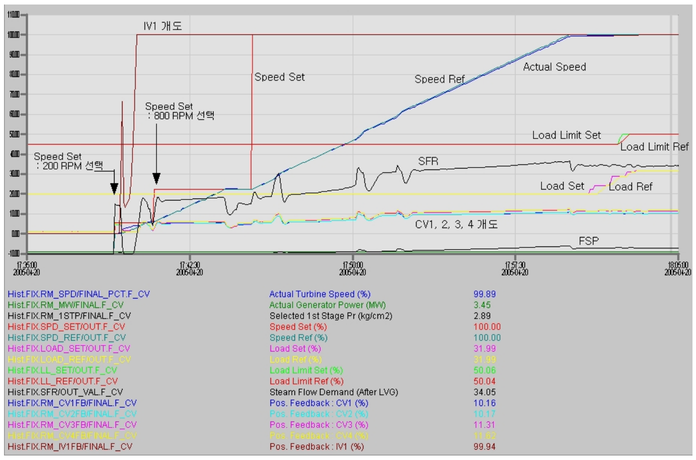

Fig. 14. Actual operation result.

VI. ACTUAL OPERATION

30 minutes trend of the actual operation without simulator are shown in Fig. 14 The procedure of actual operation is almost the same with that of pre start up with the speed target of 200, 800, 3,600 rpm. At the starting point of 200 rpm, IVs begin to open, close and open again for a short time which prevents overspeed condition. When the speed Ref. and actual speed are at 3,600 rpm (rated condition) and 3,575 rpm respectively, Load ref. was increased from 20% to 32% for the purpose that speed can be controlled at 3,600 rpm. A difference between reference and actual value rises from the fact that the speed controller is an only proportional type. The result of actual operation is similar with the one of simulation with the exception that the positions of CVs are around 5-6% during simulation test and 10-11% during actual operation [3].

Time interval of 20 minutes in horizontal axes of Fig. 13 is different from 30 minutes interval of Fig. 14 because actual operation takes long time to speed up compared with simulation. And some errors exist in control valve positions between simulation and actual operation, which result from such different operation conditions as valve position calibration error, steam pressure and steam temperature variation. Though some errors exist, the estimated parameters are meaningful because the most important point is that the soundness of the new control system was testified before actual start up.

VII. CONCLUSION

In this paper, based on energy balance, thermodynamic relations, mathematical models are developed for the steam turbine and its components. The parameters of model were estimated based on both the design data and actual operating data. It is shown that the proposed model for turbine and generator can be used for verification and validation for the newly developed control system by performing real time simulations before actual startup. Additionally, the estimated parameters are useful enough to operator education because the results of pre startup simulation and actual operation are almost the same except the speed error during actual operation is 0.11% at rated speed. This model can be used for load control algorithm, too.

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