Modeling and Simulation of the Perdawd CCGS Connected to the Kurdistan Regional Power System of Iraq Using Simulink®

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***Abstract*—A systematic procedure for modeling and simulation of the recently connected Perdawd combined cycle gas station (CCGS) to the Kurdistan Regional Power System (KRPS) of Iraq is presented in this paper. For simulation purpose, models for the station's synchronous generator, exciter system and the combined gas turbine are developed in MATLAB®/Simulink®. The stability of the system is evaluated for both small and large signal disturbances.**

***Index Terms*—Modeling, Simulation, Power System, CCGS**

I. Introduction

During the last decades there has been continuous development of combined cycle gas stations due to their increased efficiency, their low emissions, rapid installation and their low initial cost. These advantages attract the Kurdistan Regional Power System (KRPS) authorities to build a 500MW CCGS at Perdawd close to the capital load centre in Erbil to rapidly overcome the severe lack of demand in the region. But it is known that the dynamic response of such power plants to load and frequency transients is rather problematic, since the compressor and the fuel supply system are both attached to the shaft of the unit. Thus rotor speed and frequency have a direct effect on air and fuel supply, which introduces a negative effect on system stability [1]. In addition, CCGS function on the temperature limits (above a relatively low power level) so as to achieve the best efficiency in the steam generator [2]. This fact raises further issues relative to the response of combined cycle gas stations(CCGS) during frequency drops or variations at load power. Temperature should be maintained (apart from the first seconds of the disturbance) below certain limits for the protection of the plant.

This paper presents a study of Perdawd CCGS response to both small disturbances, three phase fault occur at its terminal and a three phase line outage. For this purpose, a Simulink® based block model is developed for the station, and then the model is used to evaluate the system through simulation tests in the MATLAB®/Simulink® environment.

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II. Simulink® Modeling of Perdawd CCGS

A. Synchronous Generator

The general approach to synchronous machine modeling is quite mature. Mathematical models vary from elementary classical models to more detailed ones. It depends on the nature of the study. For stability studies, the sub transient phenomena have to be captured. We have considered a d-q axis modeling of the synchronous generators in this study using IEEE conventions.

Consider an interconnected power system with m-machines and n-buses. We consider four windings on the rotor (one field and one damper in d-axis and two dampers in q axis). For i = 1 to m, the following equations represent machine dynamics [3].

$$d\delta_i / dt = \omega_i - \omega_s \tag{1}$$

$$\begin{aligned} d\omega_i / dt = \omega_s / 2H\,[&T_{mi} - D(\omega_i - \omega_s) \\ &-((X''_{di} - X_{lsi})/(X'_{di} - X_{lsi}))E'_{qi} I_{qi} \\ &-((X'_{di} - X''_{di})/(X'_{di} - X_{lsi}))\psi_{1di} I_{qi} \\ &-((X''_{qi} - X_{lsi})/(X'_{qi} - X_{lsi}))E'_{di} I_{di} \\ &+((X'_{qi} - X''_{qi})/(X'_{qi} - X_{lsi}))\psi_{2qi} I_{di} \\ &+(X''_{qi} - X''_{di}) I_{qi} I_{di}\,] \end{aligned} \tag{2}$$

$$\begin{aligned} dE'_{qi} / dt = 1/T'_{doi}\,[&-E'_{qi} - (X_{di} - X'_{di})\{-I_{di} \\ &-((X'_{di} - X''_{di})/(X'_{di} - X'_{lsi})^2) \\ &(\psi_{1di} - (X'_{di} - X_{lsi}) I_{di} - E'_{qi})\} + E_{fdi}\,] \end{aligned} \tag{3}$$

$$\begin{aligned} dE'_{di} / dt = 1/T'_{qoi}\,[&-E'_{di} - (X_{qi} - X'_{qi})\{-I_{qi} \\ &-((X'_{qi} - X''_{qi})/(X'_{qi} - X'_{lsi})^2) \\ &(\psi_{2qi} + (X'_{qi} - X_{lsi}) I_{qi} - E'_{di})\}\,] \end{aligned} \tag{4}$$

$$d\psi_{1di} / dt = 1/T''_{doi}\,[-\psi_{1di} + E'_{qi} + (X'_{di} - X_{lsi}) I_{di}\,] \tag{5}$$

$$d\psi_{2qi} / dt = 1/T''_{qo}[-\psi_{2qi} + E'_{di} + (X'_{qi} - X_{lsi}) I_{qi}\,] \tag{6}$$

Where for *i-th machine*: m is the total number of generators, δ is the generator rotor angle(rad), ω is the rotor angular speed(rad per second), E_{qi}' *is the* transient emf due to field flux-linkage(p.u), E_{di}' is the transient emf due to flux-linkage in q-axis damper coil(p.u), ψ_{1di} is the sub-transient emf due to flux-linkage in d-axis damper(p.u), ψ_{2qi} is the sub-transient emf due to flux-linkage in q-axis damper(p.u), I_{di} is

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the d-axis component of stator current(p.u), I_{qi} is the q-axis component of stator current(p.u), X_{di} X_{di}',X_{di}'' are synchronous, transient and sub-transient reactances(p.u), respectively along d- axis, $X_{q\ i}$,X_{qi}',X_{qi}'' are synchronous, transient and sub-transient reactances(p.u), respectively along q-axis, T_{do}',T_{do}'' are d-axis open-circuit transient and sub-transient time constants(second), respectively T_{qo}',T_{qo}'', are q-axis open-circuit transient and sub-transient time constants(second), respectively. This set of equations is realized in Simulink® to be used for the synchronous generator model in this paper. The relevant parameters are given in the appendix.

B. The Excitation System

The Perdawd CCGS plant is equipped with a fast IEEE STlA excitation systems. Such a type of excitation system is often modeled as a single time-constant block[4]. The error signal is used as input and E_{fd} as output. Figure 3 shows a block diagram of IEEE ST1A [4]. The SIMULINK® block for the IEEE ST1A has been built in this study, the developed model is shown in figure 4 . The parameter values are given in the appendix.

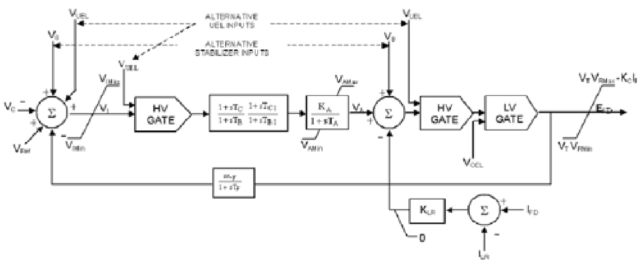

Fig.1 Type IEEE ST1A excitation system

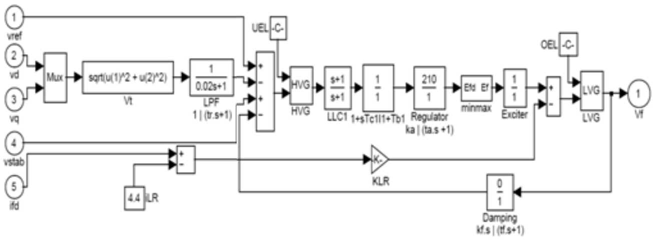

Fig.2 Simulink® model of type ST1A excitation system

A multi-band power system stabilizer (MB-PSS) is added to the excitation system. In the MB-PSS, the influences on the stabilizing signal through changes in the turbine power are also suppressed. In contrast to the PSS described above, the stabilizing signal is derived from both the rotor angular speed variation and the electrical power. Furthermore, instead of using one filter, three independent lead/lag filters are applied, which are respectively optimized for the damping of local oscillations, oscillations between network areas and global oscillations. The algorithm used in this power system stabilizer was developed by Hydro Quebec, Canada[5]. SimPowerSystem®4 supports this type of PSS and it has been used in this study.

C. The Turbine System

Several research groups proposed several dynamic models of turbine-governors with varying degrees of complexity to represent different makes and models of gas turbine units In 1983, Rowen proposed a gas turbine model for system analysis [6], and the fidelity of the model was confirmed by real measurements by Hannett and Khan in 1993 [7]. In 1994, a model of a combined cycle involving gas turbine was proposed by an IEEE working group on prime over and energy supply models for system dynamics in power system studies [8]. In 2000, Susaki and colleagues proposed a model with regard to air cooling, and compared it to an actual system by load-shedding experiments [9]. Recently, another three modified models are proposed and used in particular power system study cases[10]-[12].

In this study, another dynamical model of combined cycle plant is developed using the previous results in combination with the model proposed by IEEE committee [8].

A typical combined cycle plant configuration proposed by IEEE committee, its configuration is shown in Fig.3[8]. This arrangement is made up of an air compressor, combustor, gas turbine heat recovery boiler, and a steam turbine. This functional block diagram is considered in this study, while under block models are derived separately. The functional block diagram of Fig.3 is realized using Simulink®. It's Simulink® model is shown in Fig.4. This model is used to simulate Perdawd power plant in the rest of the study.

The turbine block in Fig.4 is based on the well known heat cycle of the gas turbine which is shown in Fig.5 [13].

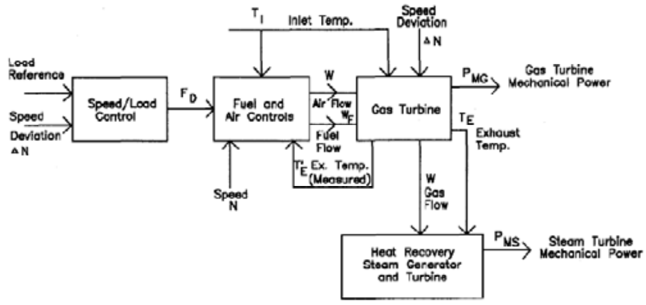

Fig.3 IEEE combined cycle model

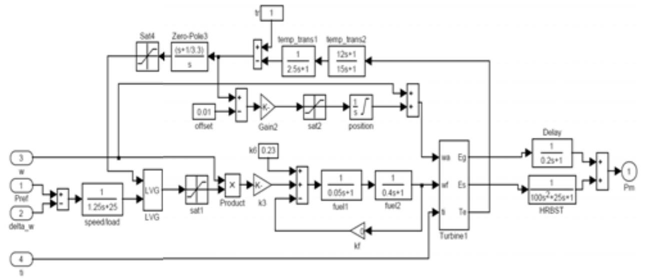

Fig.4 Simulink® model of the IEEE combined cycle model

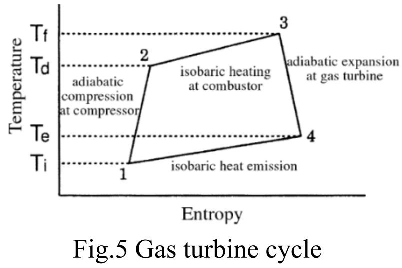

Fig.5 Gas turbine cycle

Part fragment 1–2 of the heat cycle of Fig.5 pertains to adiabatic compression of atmospheric air at the compressor, part 2–3 to isobaric heating of compressed air at the combustor, part 3–4 to driving of the turbine by adiabatic expansion of exhaust gas, and part 4–1 to isobaric cooling of the exhaust gas.

The compressor compresses air using the turbine's mechanical energy, thus increasing the pressure. With air flow inside the processor treated as an adiabatic change, the temperature T_d at the compressor's outlet can be expressed as follows[13]:

$$T_d = T_i (1 + (x - 1) / \eta_c \tag{7}$$

$$x = (P_r W_a)^{((\gamma-1)/\gamma)} \tag{8}$$

Where T_i is the temperature at the compressor inlet (assumed to be equal to the ambient temperature), W is the air flow rate, η_c is the compressor's efficiency, x is the compressor's temperature ratio, P_r is the compressor's pressure ratio, and γ is the specific heat ratio.

In the combustor, air reacts with fuel to produce high-temperature high-pressure gas. The flow rate of the combustion gas is assumed here to be the same as the air flow W. The temperature T_f at the inlet of the gas turbine is expressed as

$$T_f = T_d + (W_f / W_a) K_2 \tag{9}$$

Where W_f is the fuel flow, and K_2 is the combustor's temperature rise coefficient.

At the gas turbine, the gas pressure drops from the inlet to the outlet, and work is performed via adiabatic expansion. The temperature Te of the exhaust gas can be expressed as

$$T_e = T_f (1 - (1 - 1/x) / \eta_t \tag{10}$$

Where η_t is the turbine's efficiency.

The work done by adiabatic expansion of combustion gas in the turbine appears as the turbine's mechanical output P_{mg}. On the other hand, the compressor consumes power P_c to compress air. Therefore, the net output of the gas turbine is its mechanical output P_{mg} less the compressor's power P_c:

$$P_{mg} = K_0 (T_f - T_e) W_a \tag{11}$$

$$P_c = K_0 (T_d - T_i) W_a \tag{12}$$

$$E_g = P_{mg} - P_c \tag{13}$$

Where K_0 is the output factor of the gas turbine.

Exhaust gas from the turbine is fed to the heat recovery boiler. There is some pressure loss (for example, in the heat exchanger), which is disregarded in this model.

The output P_s of the steam turbine is determined by the temperature T_e of the gas turbine's exhaust and its flow rate W, that is,

$$E_s = K_1 T_e W \tag{14}$$

Where K_1 is the output factor of the steam turbine. The relevant parameter values of the above equations are given in the appendix.

The components model derived in previous sub-sections are integrated systematically to model a complete combined cycle power plant, hence to carry out the simulation tests.

II. SIMULATION RESULTS

In order to check the dynamic behavior of the station under study during small load fluctuations, line outage and large fault occurrence, the derived model is simulated. The simulation of the model is performed using SimPowerSystems®4 blockset of Simulink®. The solver *ode23tb(stiff/TR-BDF2)* with a maximum step size of 0.02 has been used for solving system equations[14]. The *PowerGUI* tool has been used to initialize the variables and the simulation process[15].

Following perturbations, the oscillations can be seen in many variables, we have selected the load angle, the terminal voltage and the accelerating power as assessment variables in our study. Simulation tests were carried out for three typical perturbations. The first one deals with a step change in the input mechanical power to the station, the second is three phase line outage and the third one is a three phase fault occur suddenly at the stations terminal.

Case I. Small Disturbance

To assess the damping characteristic, a small disturbance in mechanical power input is considered. The input mechanical power is increased by a step change of 5% at t=40s. The simulation configuration in Simulink® environment is shown in Fig.6. Figs.7 and 8 show the response of power angle and terminal voltage for the above case for 100s. It is clear from these two figures that the controllers including the PSS are effective in damping system oscillations and maintain system stability.

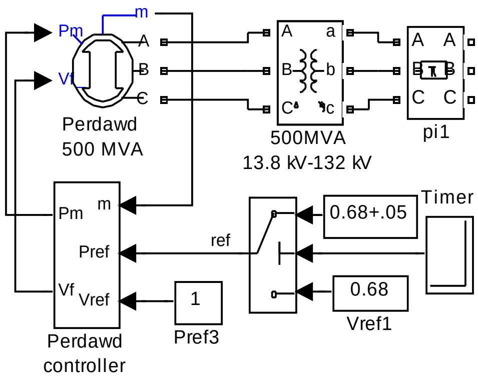

Fig.6 Simulation configuration for 5% change in the mechanical power input

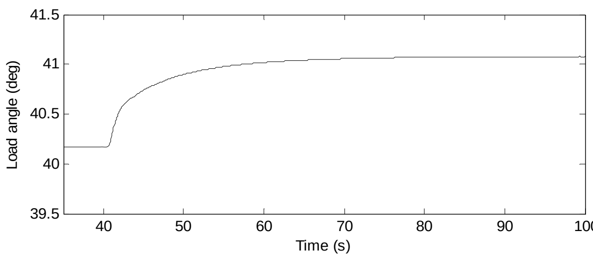

Fig.7 Load angle response to 5% change in mechanical power input

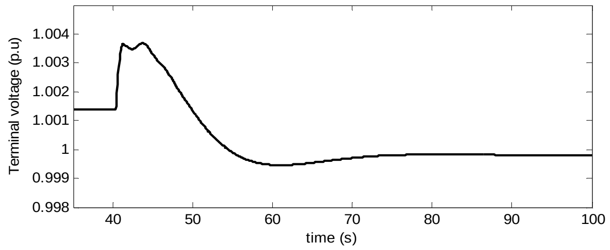

Fig.8 Terminal voltage response to 5% change in mechanical power input

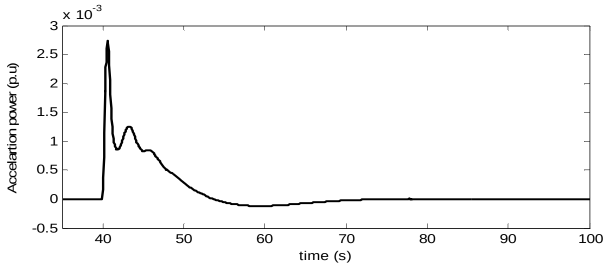

Fig.9 Acceleration power response to 5% change in mechanical power input

Case II. Large Disturbance: Three Phase Fault

A sudden three phase fault is introduced at the Perdawd generator terminal busbar at t = 0.4 s and cleared after 10 cycles (The frequency of the Iraq power system is 50 Hz). The original system is restored upon the fault clearance. The simulation configuration in Simulink® environment is shown in Fig.9, while the system load angle and terminal voltage responses for the above case are shown in Figs.10 and 11 respectively. It is clear from these figures that, the system significantly suppresses the oscillations in the power angle and provides good damping characteristics to the system oscillations by stabilizing the system quickly.

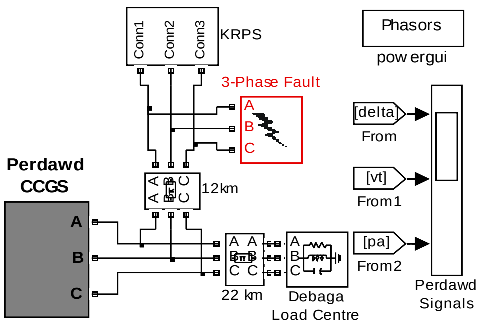

Fig.9 Simulation configuration for three phase fault

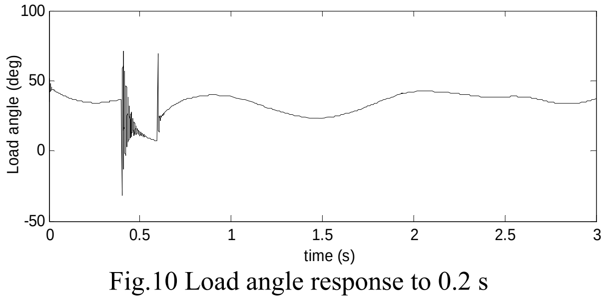

Fig.10 Load angle response to 0.2 s duration three phase fault at plant's terminal

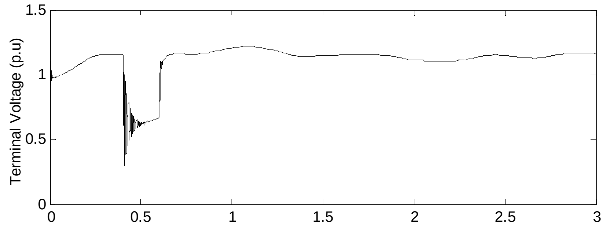

Fig.11 Terminal voltage response to 0.2 s duration three phase fault at plant's terminal

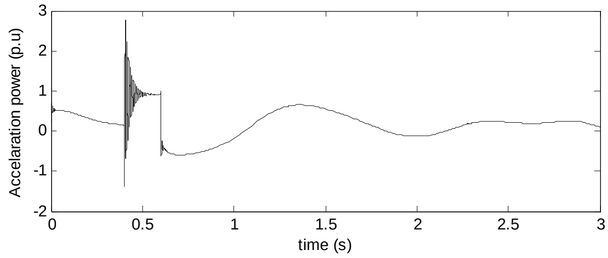

Fig. 12 Acceleration power response to 0.2 s duration three phase fault at plant's terminal

Case III. Large Disturbance: Line Outage

In this case another severe disturbance is considered. The transmission line which connects Perdawd with KRPS is permanently tripped out at t=5s.The simulation configuration in Simulink® environment is shown in Fig.13. The closest load centre at Debaga has been left unchanged during this test. This load provides a breaking torque during station;s outage. The system load angle and terminal voltage and accelerating power responses for the above case are shown in Figs.14, 15 and 16 respectively. It is also clear from the Figs. that the system is able to restore the stability after this type of disturbances; however the input-output power balance restore require 15 s with a maximum overshoot of 70%.

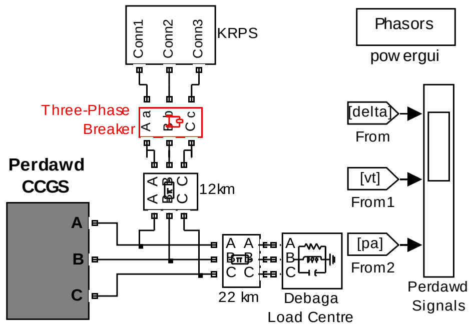

Fig.13 Simulation configuration for three phase line outage

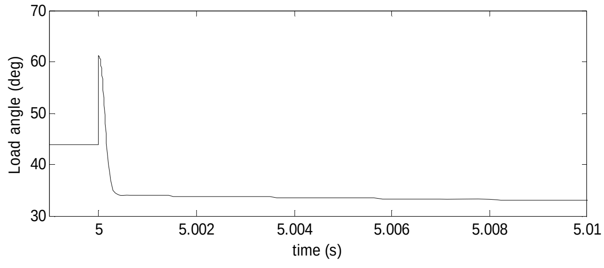

Fig.14 Load angle response to the Perdawd-KRPS tie line outage

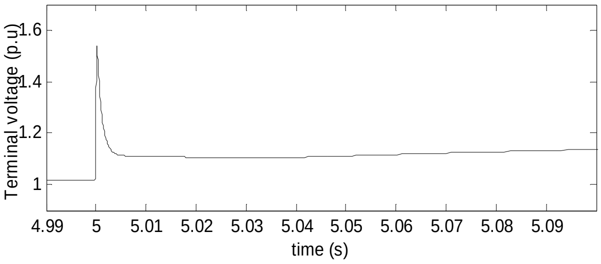

Fig.15 Terminal voltage response to the Perdawd-KRPS tie line outage

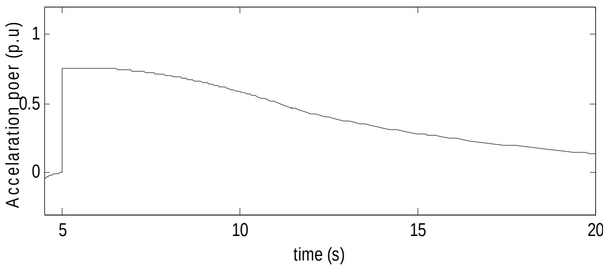

Fig.16 Acceleration power response to the Perdawd-KRPS tie line outage

III. CONCLUSION

The Perdawd CCGS components have been successfully modeled in MATLAB®/Simulink®/SimPowerSystems® environment. The simulated model and the results obtained permit to predict the performance of the station connected to Kurdistan Regional Power System.

The system dynamic behavior for both small and large disturbances is tested and their correspondence responses are recorded. The simulation results demonstrate that the established model provides a useful tool suitable to study and to perform accurate analysis of most electrical oscillation phenomenon that occurs when a CCGS is connected to a power system grid.

Simulated results show that the system with its PSS is effectively able to damp out low frequency oscillations occur during disturbances. The system is able to restore its initial operating condition when it is subjected to a three phase fault if the fault is cleared after a proper amount of time. Also it is able to maintain stability during line outages but with relatively larger percentage overshoot and settling time.

APPENDIX

The generator parameters in per unit are as follows [16]:

$$X_d = 0.8979 \quad X'_d = 0.2995 \quad X''_d = 0.23$$

$$X_q = 0.646 \quad X'_q = 0.646 \quad X''_q = 0.4$$

$$X_{ls} = 0.2396 \quad T_M = 0.8s \quad T'_{d0} = 7.4s$$

$$T''_{d0} = 0.03s \quad T'_{q0} = 0 \quad T''_{q0} = 0.033s$$

$$H = 5.148 \quad Rs = 0$$

The exciter parameters in per unit are as follows [4]:

$$K_A = 210 \quad T_A = T_C = 0 \quad T_B = 1.0$$

$$T_{C1} = T_{B1} = 0 \quad K_F = T_F = 0 \quad K_{LR} = 4.54$$

$$I_{LR} = 4.4 \quad K_C = 0.038 \quad V_{R\max} = 6.43$$

$$V_{R\min} = -6.0 \quad V_{I\,max}, V_{I\min} \ \textit{not represented}.$$

The gas turbine parameters are as follows [13]:

$$T_{i0} = 30c^{\circ} \quad T_{d0} = 390 \quad T_{f0} = 1085$$

$$T_{e0} = 505 \quad P_r = 11.5 \quad \gamma = 1.4$$

$$\eta_C = 0.85 \quad \eta_t = 0.85 \quad K_0 = 0.00303$$

$$K_1 0.000428 \quad K_2 695$$

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