Predicting Maximum Power Output of Gas Power Plants Using the Optimal Model of Genetic Algorithm

Abstract
The importance of electric energy, its increasing use, and the limited primary resources in its production have caused the importance of planning for optimal use of electricity networks and power plant production management. One of the parameters in planning the production of power plant units is knowing the production capacity and predicting the instantaneous capacity of power plants to the management of input and output of the production units. This research aimed to develop a model for forecasting the instantaneous base load of gas power plants installed and operated in large numbers. The parameters of the model were determined using an optimization method based on a genetic algorithm and its ability to predict the current capacity of the Zanjan Soltanieh power plant was evaluated. The obtained results and their comparison with the previous methods show the high capability and appropriate accuracy of the stated method to predict the instantaneous base load of gas power plants.

Keywords: Gas power plant, Maximum power output, Model, Optimization

Introduction

The increasing importance of electrical energy in human life and the development of societies have caused researchers and industrialists to pay attention to various issues in this field, especially the management and optimal planning of its production and consumption. One of the prominent features of electrical energy is the lack of storage capacity on a large scale. Therefore, the production of power plants should be planned to meet the network needs with no excess production or energy loss. In planning for the entry of power plant units, the production capability of each unit is an important parameter and must be determined with the maximum possible accuracy. Therefore, there are studies in the two fields of network load forecasting and forecasting the maximum output power. Researchers have provided many methods to predict the maximum output power by power plant units. The studies are divided into two general categories: The first group has simulated its performance based on the modeling of the power plant unit and has made a connection between the electric power inputs and output and its prediction [1-3]. The second group worked based on intelligent methods and predicted the output power of power plants using neural network theory or other intelligent optimization methods [4-6].

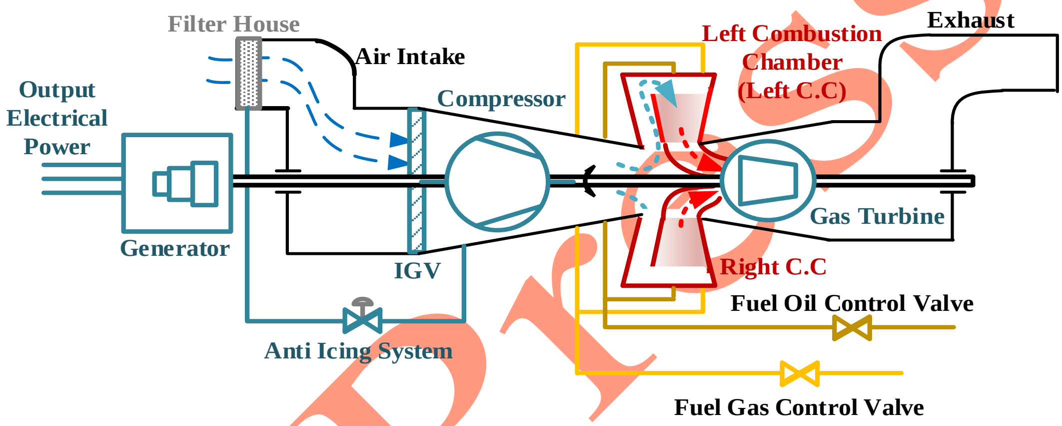


Figure 1) Gas power plant structure

Reference [7] has used a classical and traditional statistical method for short-term forecasting of the production of solar power plant units.

The authors of reference [8] have used a model based on fuzzy-neural theory to determine the output power of nuclear power plants. In reference [9], the feedforward model using a neural network was introduced to control the exhaust temperature and predict the superheat temperature. So, the producible instantaneous base load by power plant units is predicted. It should be noted that gas turbine performance is highly dependent on ambient conditions such as temperature, humidity, and pressure [10-12]. Therefore, the developed model takes into account these parameters and their influence and models the behavior of the output power in different conditions using their non-linear combination. The developed model consists of functions showing the behavior and influence of input parameters on the output. Although the relationship between the functions is nonlinear in the model, each of them is considered a linear function separately and independently. The functions were adjusted using previous samples and logs of the power plant based on the genetic algorithm. In other words, in this study, both categories of studies were used, and they can be placed in the subcategory of each. The developed method has optimized modeling with intelligent optimization methods and has introduced an effective predicting method. In the second section of the article, the operation principles of gas turbine power plant units have been described. The desired model and its parameters have been determined in the third and fourth sections, respectively. The model was performed in the Zanjan Soltanieh power plant, to check the efficiency and validity of the proposed model to predict the maximum output of the power plant. So, the function of the developed model was described in the fifth section of this study. The conclusion of the model function and simulations was described in the last section of this study.

Gas power plant

Therefore, a power plant in which steam causes the turbine to move is called a steam power plant, and a power plant whose power of fluid water causes the turbine to rotate is called a hydroelectric power plant. Therefore, in a gas power plant, a gaseous fluid applies force to the blades of the turbine and causes the rotation of the turbine. This type of power plant works based on the Brayton cycle, which is a type of thermal cycle. Figure 1 shows the structure of a gas unit. In this structure, the incoming air to the compressor is pressurized and its pressure increases about 10 to 11 times. This high-pressure air enters the combustion chambers and the thermal energy released from the fuel injected in the combustion chambers is applied to it. The fuel used by the power production units installed in Iran is natural gas and diesel, which are used as the first and second fuels. In the next step, the output hot high-pressure air of the combustion chambers is applied to the turbine blades and causes the rotation of the turbine, compressor, and generator. It should be noted that in this structure, the turbine and compressor have a single shaft that is coupled with the generator shaft. Therefore, the energy required to move the compressor and its pressurize is also provided by the thermal energy released in the combustion chambers. The compressor consumes a third of the input energy and causes a significant decrease in the efficiency of the gas unit. Half of the remaining energy is absorbed by the turbine and transferred to the generator to produce the output electrical energy and the other half of the electrical energy is released as hot air from the exhaust and is wasted. Therefore, gas units, in the best case, have 33% efficiency. Therefore, they use combined cycle units to recover wasted exhaust energy and use its heat to produce heat which is used as the input of a steam turbine and adds to the electrical energy of the complex with another independent generator. In this way, the efficiency of the system increases to an acceptable level. The gas turbine has three important parameters that must be controlled. These parameters are as follows:

- The rotor speed, which is common between the turbine and generator, and regulates the frequency of the output power.
- The output power of the generator has a direct relationship with the input power of the turbine and injected fuel.
- The inlet temperature of the turbine is directly related to the instantaneous power of the unit and the fuel injected into the chambers and needs to be controlled so that it does not exceed the maximum limit. Otherwise, the turbine blades will be seriously damaged.

The first two parameters are kept in the allowed range by the fuel valve position control. However, to control the temperature of the turbine, in addition to the use of the fuel valve control, the inlet air flow rate is also controlled to keep the turbine temperature in a safe range, and the turbine blades are operated in a suitable condition.

The base load predicting model

The compressor inlet has an adjustable vane row, which is called IGV. These vanes are considered closed at an angle of 143 degrees with the horizon and are completely open at an angle of 103 degrees. This equipment is used to control the airflow of the compressor. In loading the unit, with increasing load, more fuel is injected into the chambers and causing the increased temperature of the turbine. In this case, the governor opens the IGV to allow more air to enter the turbine and reduce the temperature. Therefore, as the load increases, the IGV also opens step by step until finally it opens completely and the governor is no longer able to use it to control the temperature of the turbine. In this state, the unit has reached its maximum power, which is called base load. Therefore, the base load is the maximum output power of the turbine according to its temperature limit. Therefore, all factors and parameters that cause the turbine to reach its maximum temperature later can be effective in determining the base load of the unit and should be included in the instant base load forecasting model. Figure 2 shows the parameters. According to turbine manufacturers, the ambient and mechanical factors described in Figure 2 affect the rated power of the turbine.

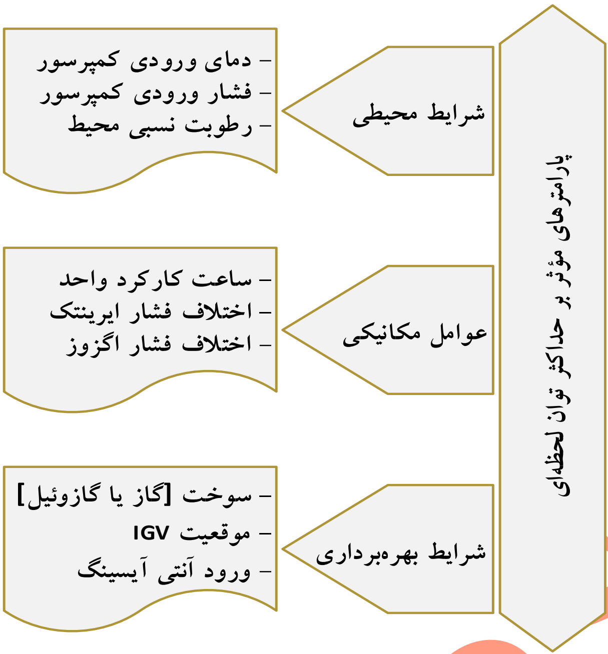


Figure 2) Factors affecting the maximum instantaneous power

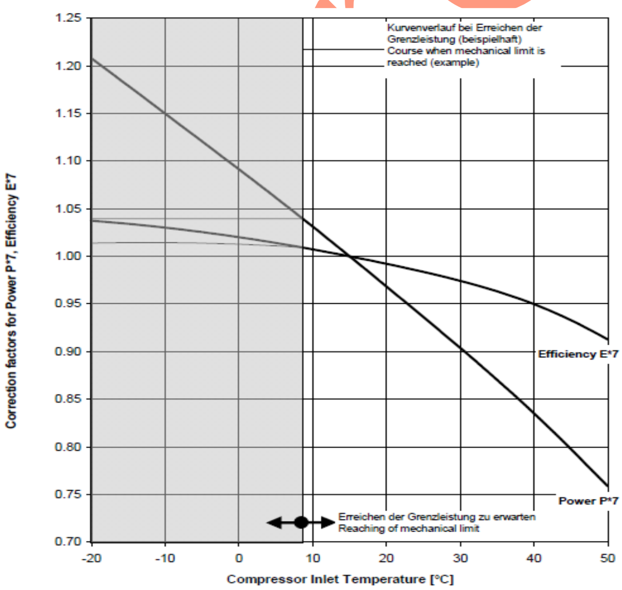


Figure 3) Temperature coefficient of gas turbine output rated power [13]

In other words, the turbine has a nominal power measured in reference conditions (conditions stated in Table 1). By changing any of the factors, the power will change. Each of these six parameters has a coefficient that is multiplied by the rated power and results in the output power of the turbine in the environmental conditions at the installation site. It needs to refer to the specifications provided by the manufacturer to determine the coefficients based on the environmental and mechanical conditions of the installed power plant unit. Figure 3 shows the corresponding characteristic concerning the ambient temperature [13]. Another parameter affecting the output power of the unit is the operating parameters shown in Figure 2. Meanwhile, one of the effective factors is the consumed fuel type of the unit. Indeed, the calorific value of diesel is different from natural gas and creates a different combustion temperature. Therefore, the temperature limit considered for the governor must be different in two types of fuel and the turbine controller of the power plant unit determines the permissible limit of the temperature controller according to the consumed fuel. Experience has shown that diesel fuel has a lower temperature limit than natural gas and the output power of the unit with diesel is about 2 megawatts less. Another operating parameter affecting the output power of the unit is the IGV+ capability.

IGV is a dynamic and controllable vane used at the compressor inlet and controls the input air. The blades of this section have an angle of 103 degrees in the fully open position. However, using this feature, the IGV of the unit can be opened a little more and placed at a 96-degree angle with the horizon in its fully open state. This feature is called +IGV. By placing the unit in this position, more air enters the compressor and turbine and reduces the turbine inlet temperature. So, the unit reaches its upper-temperature limit later and can produce 2 to 4 MW more electricity (depending on mechanical and environmental conditions). Another operating factor affecting unit losses and its output power that is neglected in most studies is the anti-icing system of input air. This is an anti-icing operating factor. The principles of gas turbine operation state that the lower the inlet temperature of the unit, the higher the efficiency of the unit. However, it should be noted that if the inlet temperature is lower than a certain limit and the ambient humidity is high, it will severely damage the compressor and reduce the equipment lifecycle. Therefore, the anti-icing system is installed to transfer part of the hot air from the middle stages of the compressor to the air system inlet and prevent the entry of cold and humid air. This system is used frequently in winter and units installed in cold regions reduce the output power. These losses can reach 10% of unit production. Therefore, the maximum output power should be taken into account in the proposed model. The model shown in Figure 3 can be suggested as a model for predicting the base power of a gas turbine unit.

Table 1) Reference conditions for determining the rated power of the turbine [13]

Parameter	**Unit**	**Value**	**Parameter**	**Unit**	**Value**
Ambient pressure	mBar	1013	**Power factor**	-	**0.8**
Ambient temperature	°C	15	**Frequency**	Hz	**50**
Rotor speed	rpm	3000	**Generator output terminal voltage**	kV	**15.75**
Ambient relative humidity	%	60			

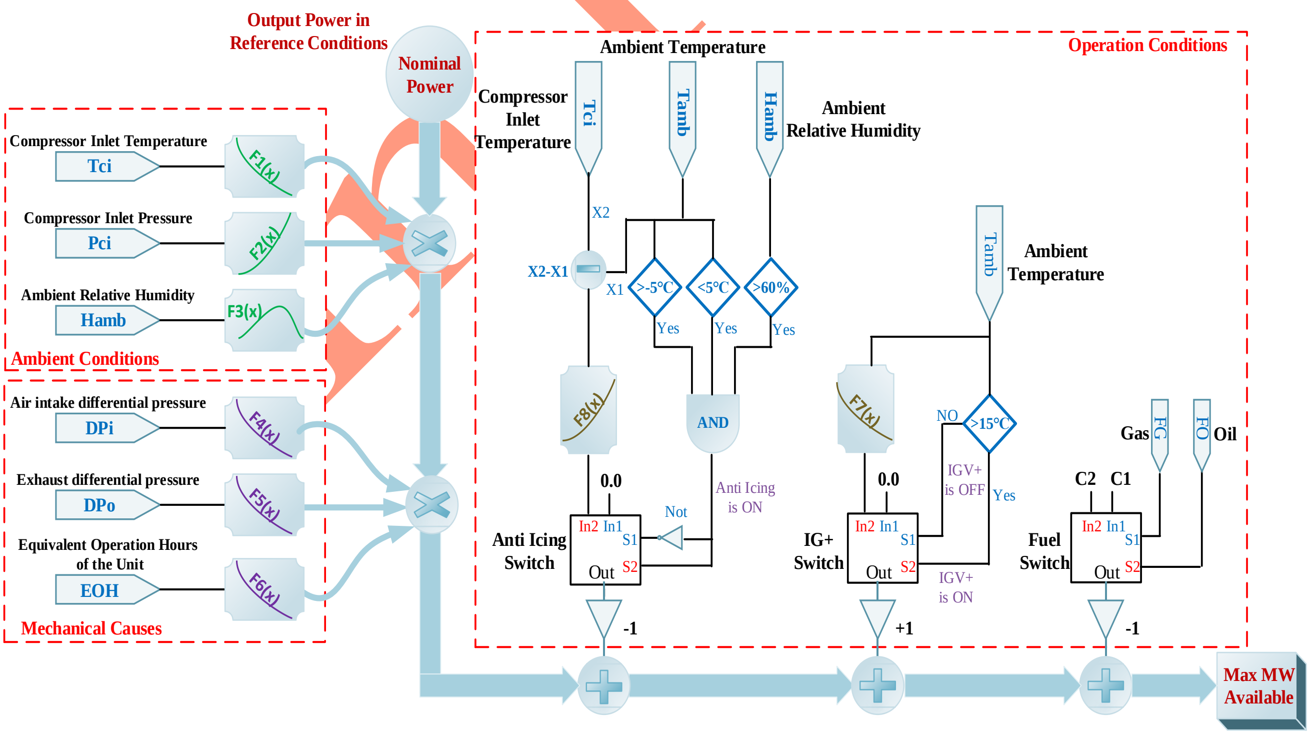


Figure 4) Predictive model of the producible maximum power by the gas power plant unit

Model parameters

The predictive model shown in Figure 4 shows the dependence of the producible maximum power by the gas power plant on the nine factors shown in Figure 2. The curves provided by the turbine manufacturer are used to determine the effect of each of the factors. So, the influence coefficient is determined according to the conditions and characteristics.

This method has the following problems:

- No characteristic is provided for the mentioned operating factors, and their effect is shown with a fixed number, which is often accompanied by an error.

- The features provided for all turbines of a manufacturer are unique and each turbine does not have a specific feature; whereas, their behaviors are different and the use of a single curve can cause a major error to estimate the maximum output power produced by the unit. The measurement error of the equipment is not taken into account to determine the influence coefficient of the factors, using the manufacturer's features. In other words, in two power plant units whose measurement equipment has a different error, a different influence coefficient will be extracted and the calculations will be erroneous in similar conditions.

- The presented characteristics are often curved and non-linear and its implementation in industrial controllers has limitations. So it makes a problem for the continuous prediction that is the need of the network and its management.

To solve the mentioned problems, the manufacturer and unique features can be left out and accurate features can be extracted for each power plant unit concerning the inherent features and ambient conditions of its installation location and all installed measuring equipment with their errors and characteristics.

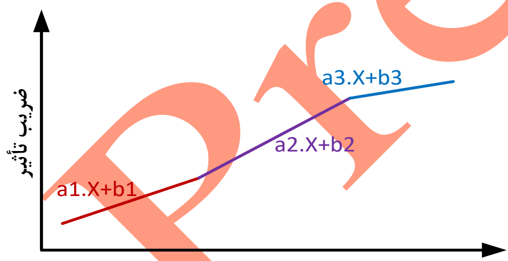


Figure 5) Basic feature

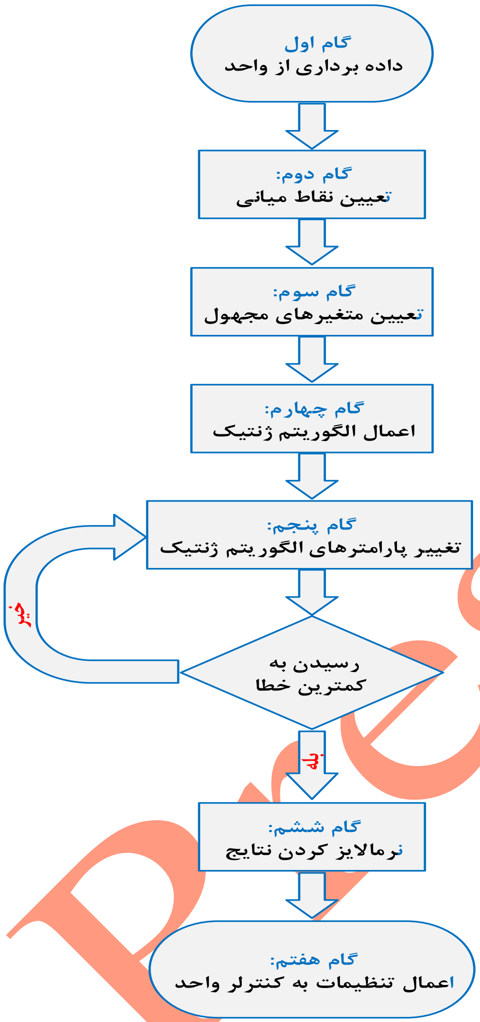


Figure 6) Algorithm for extracting the model parameters

Step 1: Applying settings to the controller unit

In this regard, the features of each of the determined factors are assumed as shown in Figure 5 and its parameters are extracted using the records of the unit in the last year. An optimization method based on a genetic algorithm was used to determine the unknown parameters and the results with the least error are applied as the final output to the settings of the unit's control system. The algorithm shown in Figure 6 describes the steps to determine the relevant model settings step by step.

These stages include:

The first step (data collection from the unit): All the information of the unit is stored in the form of logs on servers and depending on the amount of exported messages, they can store the unit log for 6 months to 2 years. In other words, if the number of equipment operations and their errors is less, fewer messages will be issued and it occupies less space and the storage server can store older data. The information on unit power, ambient pressure, ambient temperature, ambient humidity, compressor inlet temperature, unit operating hours, unit fuel, IGV+ status, and anti-icing status should be recognized and stored in the system. In extracting the information, it should be noted that the working points of the unit are acceptable for data collection, in which the unit has been for more than 2 hours and with one fuel type at the base load.

Step 2: Determining the middle points

The default attribute of each parameter can be a combination of 2 or 3 lines. In this case, the intersection of the lines is called the midpoint. One of the important steps of implementing this method is to correctly determine these points. This depends on the data frequency, and the more the number of data, the more intermediate points can be selected and the accuracy of the model

performance can be improved. Midpoints should be chosen in such a way that there is enough sample within the determined limits and the estimation of the relationship has a suitable accuracy.
Step 3: Determination of unknown variables
By determining the number of intermediate points, the features of each parameter and the number of its lines are specified. In this step, the relation of each line is defined according to relation (1):

$$a_{ij} X + b_{ij} \tag{1}$$

In this relation, *i* is the index of the parameter (for example, it is 1 for the inlet temperature of the compressor) and *j* is the line number index in that parameter.
Step 4: Applying the genetic algorithm
An optimization program with the objective function stated in relation (2) can be developed based on the genetic algorithm by determining the inputs of the system (the 9 parameters) and its output (base power of the power plant unit). In this way, the unknown parameters stated in the previous step are determined with the least error.

$$ObjectFunction : Min(F)$$
$$F = \sum_{k=1}^{N} MMA_k - MW_k \tag{2}$$

$$MMA = [(a_{1k1} T_{ci} + b_{1k1})(a_{2k2} P_{ci} + b_{2k2})(a_{3k3} H_{amb} + b_{3k3}) \\ (a_{4k4} DP_i + b_{4k4})(a_{5k5} DP_o + b_{5k5})(a_{6k6} EOH + b_{6k6})] P_{nom} \\ - C_{AntiIcing} + C_{IGV} - C_{Fuel} \tag{3}$$

Step 5: Changing the genetic algorithm parameters
The genetic algorithm has parameters such as the number of initial vectors (population), the number of bits (chromosomes) of each gene, the number of selected vectors, the number of vectors resulting from the crossover, and the number of vectors resulting from mutation. Changing each of the parameters can be effective in the final result and obtaining an answer with the least error. In this step, the specification of the algorithm is changed to choose the best mode among the different modes of algorithm execution.
Step 6: Normalizing the results
All features must pass point 1 in the standard conditions described in Table 1. However, a random feature of optimization algorithms will remove this feature from the results. Therefore, all curves of environmental and mechanical parameters will be normalized using multiplied by the following correction coefficients.

$$CF_T = \frac{1}{F_1(15)}$$
$$CF_P = \frac{1}{F_2(1013)} \tag{4}$$
$$CF_T = \frac{1}{F_3(60)}$$
$$CF_{DPI} = CF_{DPO} = CF_{EOH} = \sqrt[3]{\left(\frac{1}{CF_T.CF_P.CF_{EOH}}\right)}$$

Step 7: Applying settings to the unit controller
The controller of most gas units has a polygon function called PLG. A polygon is considered for each of the obtained functions and the obtained results are applied to them.

Table 2) Specifications of the genetic algorithm in the studied sample

Parameter	Number	Parameter	Number
Response vectors	100	Selected vector	40
Bits of each asset	10	Intersection vectors	30

Repetition	200	Mutation vectors	30

Applying the introduced method to a sample power plant

The researcher evaluated and validated a newly developed method or structure. In this regard, the methods that have the possibility of practical implementation are evaluated in a laboratory or industrial way, otherwise, they are verified using simulation. In this regard, the methods with the possibility of practical implementation are evaluated in a laboratory or industrial way, otherwise, they are verified using simulation. In this research, the developed model was applied to Zanjan Soltanieh power plant units and its ability was evaluated to predict the instantaneous base power of the power plant units. Table 3 shows the data collected from Unit 3 of the power plant in one year. It should be noted that the sampling was carried out on 50 work points, however, only 10 samples were mentioned in table 3. The results shown in Table 4 are obtained by applying the extracted samples to the optimization program based on the genetic algorithm with the specifications stated in Table 2. Table 2 shows the settings of functions of 9 parameters affecting the maximum instantaneous power shown in Figures 3 and 4.

Table 3) Examples of data extracted from the studied power pklant unit (Unit 3 of Zanjan Soltanieh Power Plant)

No.	Date	Time	Power (MW)	Compressor Inlet Temperature (°C)	Ambient. Temperature (°C)	Ambient Pressure (mBar)	Ambient Humidity (%)	Equivalent Operation Hours	Fuel	+IGV	Anti-Icing
1	2019.06.23	14	118.50	30.19	32.86	783.64	18.78	46462	Gas	ON	OFF
2	2019.07.20	17	115.60	31.59	37.18	783.72	15.83	47113	Gas	ON	OFF
3	2019.08.01	20	114.27	29.69	30.62	778.12	26.82	47420	Gas	ON	OFF
4	2019.09.19	16	115	28.00	35.49	784.68	15.00	48600	Gas	OFF	OFF
5	2019.11.18	21	123.74	6.99	3.86	781.04	66.61	50134	Oil	OFF	ON
6	2020.01.04	23	116.97	8.51	1.11	774.44	72.55	50769	Oil	OFF	ON
7	2020.01.26	20	140.81	-6.39	-5.44	780.96	52.91	51271	Gas	OFF	OFF
8	2020.02.20	14	116.47	10.81	3.59	774.08	77.94	51843	Oil	OFF	ON
9	2020.04.08	22	126.78	6.62	0.59	783.4	60.98	52583	Gas	OFF	ON
10	2020.05.04	14	130	17.67	21.51	782.6	23.62	53142	Gas	ON	OFF

Table 4) Specifications of the genetic algorithm in the studied sample

Ambient Conditions					
F1(x)		**F2(x)**		**F3(x)**	
-20.00	1.222	750.00	0.7199	0	1.0123
19.99	0.9693	779.99	0.7546	49.99	1.0125
20.00	0.9703	780.00	0.7596	50	0.9968
50.00	0.7466	850.00	0.8361	100	1.0128
Mechanical Causes					
F4(x)		**F5(x)**		**F6(x)**	
X	Y	X	Y	X	Y
0	1.04542	0	1	0	1
6	1.03593	10	0.9948	700	1
10	1.02960	20	0.9896	33000	0.99985
20	1.01379	30	0.9845	66000	0.99970
Operation Conditions					
F7(x)		**F8(x)**		**F9(x)**	
X	Y	X	Y	X	Y
15	5.9511	0	0	C1	1.7644
40	4.8513	10	9	C2	4.7585

The maximum power producible by the studied power plant unit was predicted by the above two methods for the states described in Table 3 to compare the introduced method with the previous method based on manufacturer specifications, and the results of this simulation were shown in Table 5 and Figure 7. The results show the excellent performance of the proposed method in comparison with the previous method. Especially when anti-icing is activated, the performance accuracy of the previous method is much lower and there is a huge difference in the actual performance of the unit. This can be seen in the failure to predict the system's performance by the manufacturer.

Table 5) Performance comparison of the proposed method with the previous method

No.	Power (MW)	Previous Method (MW)	Previous Method Error (%)	Presented Method (MW)	Presented Method Error (%)
1	118.50	121.56	-2.58	117.99	0.43
2	115.60	120.92	-4.60	115.99	-0.34
3	114.27	120.75	-5.67	115.28	-0.88
4	115	121.29	-5.47	114.38	0.54
5	123.74	135.18	-9.25	124.82	-0.87
6	116.97	132.62	-13.38	118.11	-0.97
7	140.81	149.28	-6.02	140.96	-0.11
8	116.47	130.67	-12.19%	117.53	-0.91
9	126.78	137.77	-8.67	125.81	0.76
10	130	131.90	-1.46	128.99	0.77

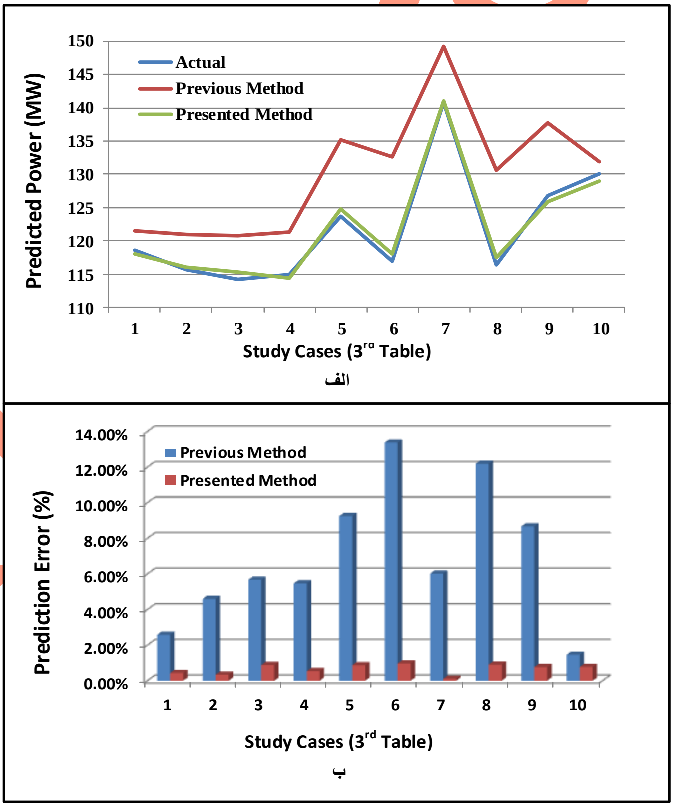
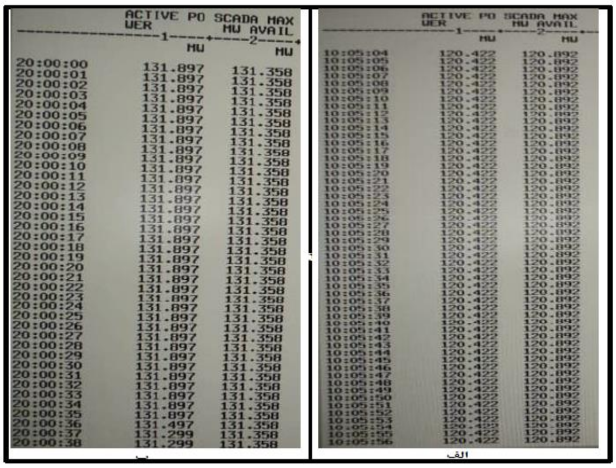


Figure 7) Performance evaluation of the proposed optimal model: A- Performance comparison of the proposed method and the previous method, b- comparison of the prediction error of the proposed method and the previous method

Another point worth mentioning is that the performance of the proposed method is within the permissible range. In other words, if according to the rules defined by the management of Iran's electricity network, the maximum allowed error of this forecast is 1%, so the proposed method has predicted the maximum power producible by the power plant unit in all the states described in Table 3 with a permissible accuracy. While the previous method in its best performance has a significant distance from the permissible range. Figures 8 and 9 show the results of the practical implementation of the introduced model along with the settings obtained from the optimization described in Unit 3 of the Zanjan Soltanieh Power Plant. These figures confirm the simulation and show the high accuracy of the introduced method to predict the maximum instantaneous power of gas units.



	ACTIVE POWER MW	SCADA MAX MW AVAIL MW
20:00:00	131.897	131.358
20:00:01	131.897	131.358
20:00:02	131.897	131.358
20:00:03	131.897	131.358
20:00:04	131.897	131.358
20:00:05	131.897	131.358
20:00:06	131.897	131.358
20:00:07	131.897	131.358
20:00:08	131.897	131.358
20:00:09	131.897	131.358
20:00:10	131.897	131.358
20:00:11	131.897	131.358
20:00:12	131.897	131.358
20:00:13	131.897	131.358
20:00:14	131.897	131.358
20:00:15	131.897	131.358
20:00:16	131.897	131.358
20:00:17	131.897	131.358
20:00:18	131.897	131.358
20:00:19	131.897	131.358
20:00:20	131.897	131.358
20:00:21	131.897	131.358
20:00:22	131.897	131.358
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20:00:24	131.897	131.358
20:00:25	131.897	131.358
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20:00:27	131.897	131.358
20:00:28	131.897	131.358
20:00:29	131.897	131.358
20:00:30	131.897	131.358
20:00:31	131.897	131.358
20:00:32	131.897	131.358
20:00:33	131.897	131.358
20:00:34	131.897	131.358
20:00:35	131.897	131.358
20:00:36	131.497	131.358
20:00:37	131.299	131.358
20:00:38	131.299	131.358

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	ACTIVE POWER MW	SCADA MAX MW AVAIL MW
10:05:04	120.422	120.892
10:05:05	120.422	120.892
10:05:06	120.422	120.892
10:05:07	120.422	120.892
10:05:08	120.422	120.892
10:05:09	120.422	120.892
10:05:10	120.422	120.892
10:05:11	120.422	120.892
10:05:12	120.422	120.892
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10:05:26	120.422	120.892
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10:05:50	120.422	120.892
10:05:51	120.422	120.892
10:05:52	120.422	120.892
10:05:53	120.422	120.892
10:05:54	120.422	120.892
10:05:55	120.422	120.892
10:05:56	120.422	120.892

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Figure 8) Comparison of instantaneous power (left column) and predicted power (right column) in the practical implementation of the proposed method: a- summer; b- winter

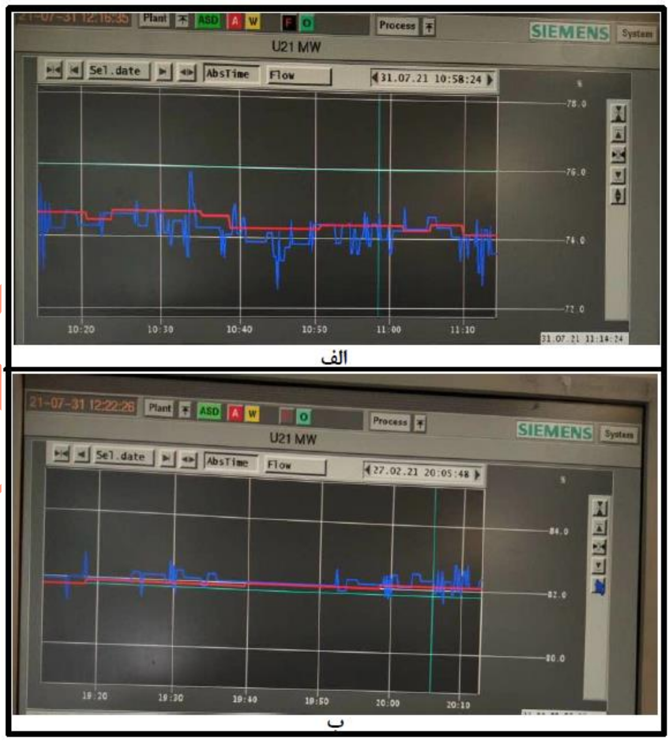

Figure 8) Comparison of current power (blue) and predicted power (red) in the practical implementation of the proposed method: a- summer; b- winter

Conclusion

The correct prediction of the maximum power producible by power plant units is considerable to the management of the production and consumption of a power network. In this study, a model based on the parameters affecting the performance of gas units has been presented to predict the maximum base power of gas power plant units. The parameters of this model depend on the environmental and mechanical conditions of the installation of the power plant unit, and it is not possible to consider general and comprehensive settings for all units in the network. Therefore, to determine these parameters, a method based on an optimization problem has been defined and solved using a genetic algorithm. The results obtained from the simulation and practical implementation of the presented model in the case study show the high accuracy and performance of this method in different months of the year with different environmental and operating conditions.