The Journal of Engine Research, Vol. 42 (Spring 2016), pp. 43-50

The Journal of Engine Research

Journal Homepage: www.engineresearch.ir

ANN Model to Predict the Performance of a Diesel Power Generator Fueled with Biodiesel

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ARTICLE INFO

Article history:
Received: 24 July 2015
Accepted: 6 June 2016

Keywords:
ANN
Biodiesel
Performance Parameters
Diesel Power Generator
Engine Load

ABSTRACT

Alternative fuels are intensively investigated for the replacement of the diesel fuel. Today the diesel power generators are mostly used in the various industrial companies in Iran. Therefore, it is necessary to estimate the level of performance of the diesel power generators fueled with biofuels. For the first time, in this study, the prediction of the performance of a diesel power generator was carried out for different neural networks to define how the inputs affect the outputs using the biodiesel blends produced from waste cooking oil. The different diesel-biodiesel blends with were used to measure the engine performance for different engine loads at the rated engine speed. In this paper, Artificial Neural Network models are proposed for the prediction of brake power, brake torque, BTE and BSFC. The coefficient of multiple determination values are found to be above 0.95 for all the models. It is evident that the ANN models are reliable tools for the prediction of the performance of diesel power generator.

1) Introduction

The engine piston as the movable wall of the combustion chamber is affect by high pressure and temperature resulted from explosion of air-fuel mixture which may reach about 180-200 bar for diesel engines and less than 70 bar for gasoline engines [1]. It is noted that the components subjected to high temperatures lose their stiffness and strength due to decrease in amount of Young modulus and yield point [2]. Temperature distribution also leads to further thermal deformations and thermal stresses and has a crucial role in amount of generated frictional effects on the piston skirt region [3]. So, the piston should be well designed to withstand the thermal and mechanical stress resulted from extreme heat and pressure of the combustion chamber.

In modern engines, the desire to increase thermal efficiency makes it tempting to adopt higher compression ratios [4]. It seems an appropriate strategy for promoting the older engines like XU7 with widespread use in Iran. However, severe resulted heat and pressure in the combustion chamber should be considered so that the hardness and strength of the parts would not be destructively affected [5].

Computer simulations of the piston are very useful and economically viable for reducing the time and cost at design stage of the engine before the first prototype is constructed. There are many research papers on the calculation of temperature distribution. Cerit and Soyhan showed that the maximum temperature on the top surface of aluminum and steel coated with ceramic layer may diminish and, compared to the clean piston [6]. Using a three dimensional finite element model, Li [7] proved that the operating temperatures on skirt region play an important part in reduction of scuffing and friction. Tahar Abbes et al. [8] presented the thermo-mechanical behavior of a direct-injection diesel engine piston subjected to the combined thermal and mechanical loads. Bohac et al. [9] used a resistance-capacitance model for steady state and transient heat transfer of gasoline engines. Using Matlab software, Ghasemian and Jazayeri evaluated the effect of cooling system performance on temperature distribution of a specified gasoline engine [10]. Gharloghy and Kakaee successfully investigated the effect of boundary conditions and rings on temperature distribution of an EF7TC engine [11]. Pourhamid et al. showed that the pistons and cylinders made of combination ceramics and metals, known as functionally graded materials, have better wear properties and thermal insulations [12].

Thermal ceramic coatings are commonly applied to insulate the substance surfaces to allow for higher operating temperatures and protecting the metallic surfaces from thermal stresses during the power and exhaust strokes of both diesel and gasoline engine cycles [13, 14]. However, one of the main characteristics of the ceramics is brittleness and residual thermal stress leads to spallation of coatings [15].Therefore, it is very important to determine the thermal and mechanical stresses occurred in the piston for instantaneous heating and cooling the piston. However, thermo-mechanical stress analyses for the engine pistons are limited [1].

In this paper, a thermo- mechanical investigation is presented for evaluating the stress distribution of an aluminum piston assembled in XU7 gasoline engine. Several thicknesses of ceramic layers are studied to achieve the optimum engine performance. The results are then compared with the results of the uncoated piston to evaluate the contribution of coating layer to better engine performance. The effect of thermal condition of lubricating oil on stress and deformation fields of the engine piston is also investigated in this work.

2) Materials and methods

2.1) Biodiesel preparation and fuel properties

Since biodiesel from waste vegetable cooking oil is a more economical source of the fuel in the present investigation, in this research, biodiesel was produced from this source [19, 20].

In the present research, biodiesel was produced by a transesterification process which was catalyzed by KOH (as Alkali catalyst) and methanol (as alcohol). Then, biodiesel was analyzed by an established research institution following the ASTM D6751 standard. The important properties of waste vegetable cooking oil and No. 2 diesel are shown in Table 1.

Table 1: Properties of diesel and biodiesel fuels used for present investigation

Property	Method	Units	Biodiesel	Diesel
Flash point	ASTM-D92	°C	176	61
Pour point	ASTM-D97	°C	-4	0
Cloud point	ASTM-D2500	°C	-1	2
Kinematical viscosity,40°C	ASTM-D445	mm^2/s	4.15	4.03
Copper strip corrosion	ASTM-D130	--------	1a	1a
Density	---------	Kg/m^3	880	840
Lower Heating Value	---------	MJ/kg	37.7	42.9

2.2) Test engine experimental setup, procedure and performance characteristics calculation

In this study, the engine tests were carried out on a diesel power generator model CAT3412 consisting of a four-stroke, supercharged diesel engine coupled to an instrumented generator to evaluate the engine performance characteristics. The generator was equipped with a central processing system and a control panel to record the data. Also a system with scale method was used for determination of engine fuel consumption. The major specifications of the internal combustion engine are shown in Table 2.

Table 2: Specifications of the test engine

Engine type	Diesel power generator CAT3412
Cylinder number	12
Stroke(mm)	154
Bore(mm)	137
Compression ratio	13: 1
Cooling system	Water cooled

The characteristics of the generator are: maximum power – 330kVA; voltage – 380V; three-phase; rotation – 15300rpm, Armature rotor resistance–0.1 Ω, and Stator resistance–0.15 Ω. Also the power factor of 0.90 was used.

The diesel engine was fuelled with blends of biodiesel and No. 2 diesel fuel. The fuel blends were used at the constant engine speed and different electrical load. The engine was allowed to run for a few times until the exhaust gas temperature, the cooling water temperature, the lubricating oil temperature have attained steady-state values and then the data were recorded. In this research, Armature rotor resistance and stator resistance were considered to calculate of engine brake power. Based on the engine brake torque, the engine speed and the fuel mass flow rate and lower heating value of fuel, the brake power, the brake specific fuel consumption (BSFC) and the brake thermal efficiency (BTE) were calculated.

2.3) Artificial neural network (ANN)

In this study, a multi-layer perceptron (MPL) in which all of the neurons were connected to each other was utilized. This model is widely used in nonlinear modeling due to its simplicity and high accuracy. Different transfer functions such as sigmoid (logsig), logarithm (tansig), linear (purelin) and supervised learning algorithms, as well as Feed Forward Back Propagation (FFBP) networks such as Levenberg–Marquardt (trainlm) and “trainscg” algorithms were usedand their corresponding results were compared together.

The input values to the ANN were firstly normalized and then divided randomly into three groups, namely, train (70 %), validation (15 %) and test (15 %). The required code for ANN simulation was developed in MATLAB software version R2013a.The best topology for the ANNs was determined based on two criteria including coefficient of determination (R^2) and Mean Squared Error (MSE). The best fitting for estimation of energy consumption for food and beverage industries is one that has largest R^2 and smallest MSE. The R^2 and MSE values were calculated using the following equations:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{n} (a_i - p_i)^2}{\sum_{i=1}^{n} (p_i)^2} \right]^{\frac{1}{2}} \qquad (1)$$

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (a_i - p_i)^2 \qquad (2)$$

Where a_i is the actual value, p_i the output value and n the number of data values.

The ANNs model was carried out to reach brake power, brake torque, fuel consumption and thermal efficiency. The input variables to the model were load engine and diesel fuel blends.

3) Results and discussion

Several topologies (2160 number) were evaluated to obtain maximum R^2 and minimum MSE values. The best topology was 2 hidden layers (11-4), using Levenberg-Marquardt (LM) learning algorithm and tangent-sigmoid transfer function would provide an efficient response to predict the output parameters. The best coefficient of determination and mean square error were reported in table (3).

Table 3: The best coefficient of determination and mean square error in different steps of artificial neural networks with 11-4 topology

Step	Statist. Index	BP	BTT	BSFC	TE
Train	R2	0.97	0.98	0.99	0.96
	MSE	0.128	1.381	0.034	0.234
Validation	R2	0.95	0.98	0.99	0.92
	MSE	0.245	1.373	0.042	0.472
Test	R2	0.98	0.97	0.99	0.96
	MSE	0.097	1.461	0.026	0.293

In the present research, artificial neural networks can predict and estimate fuel consumption value better than other dependent variables, so that this network has the highest coefficient determination and lowest mean square error in estimating of fuel consumption.

In other section of this research, relations between load engine and fuel blend with brake power, brake torque, fuel consumption and thermal efficiency were calculated and regression models were presented in Table (4).

As the tables (3 and 4) showed that accuracy of regression models and artificial neural network have no difference to each other. But artificial neural networks have an important superiority than that of regression models. ANN can estimate four independent variables in one model but regression can estimate them in four separate models, so ANN is the selected and suggested model in present research.

Table 4: The best regression models for estimating of dependent variables (X1 and X2 are engine load and fuel blend respectively)

Dependent variables	Regression model	R2	MSE
Brake Power	$-1.62+0.3X_1+80.7X_2-0.004X_1X_2+9.08X_1^2+0.2X_2^2$	0.97	0.229
Brake Torque	$-20.4+2.16X_1+500.7X_2-0.02X_1X_2+40.1X_1^2+1.1X_2^2$	0.98	2.017
Brake specific fuel consumption	$1095.5-19.412X_1-1.525X_2-0.029X_1X_2+0.114X_1^2+0.0565X_2^2$	0.97	0.082
Brake thermal efficiency	$-2.28+0.51X_1+0.21X_2-0.0011X_1X_2-0.00175X_1^2-0.00227X_2^2$	0.96	0.681

In Figs. 1–4, the actual and predicted values for all the outputs are compared. In these figures, the X-axle indicates the actual data and the Y-axle shows the predicted values. As shown in the figures, the actual and predicted values are very close to each other. But some test data and predicted values for performance parameters are not very close to each other. It can be due to the complexity of the burning process and the measurement errors[5].

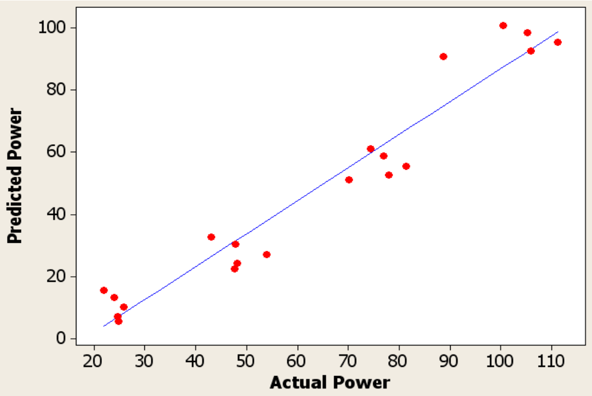

Figure 1: Comparisons of the ANN-predicted results and experimental (actual) results for brake power

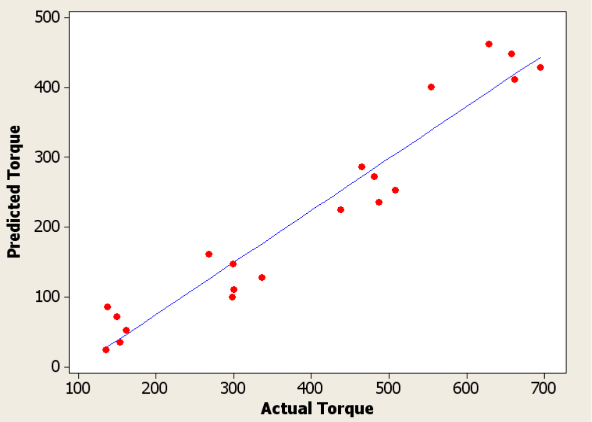

Figure 2: Comparisons of the ANN-predicted results and experimental (actual) results for brake torque

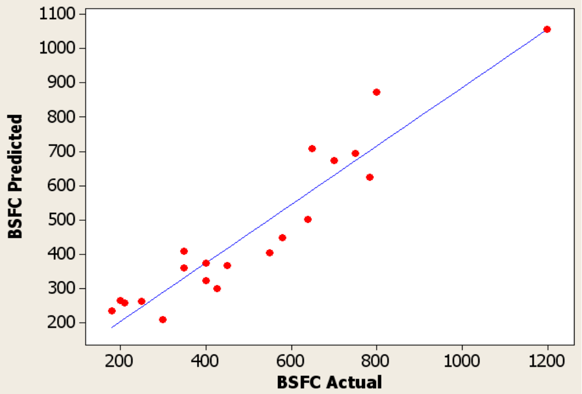

Figure 3: Comparisons of the ANN-predicted results and experimental (actual) results for BSFC.

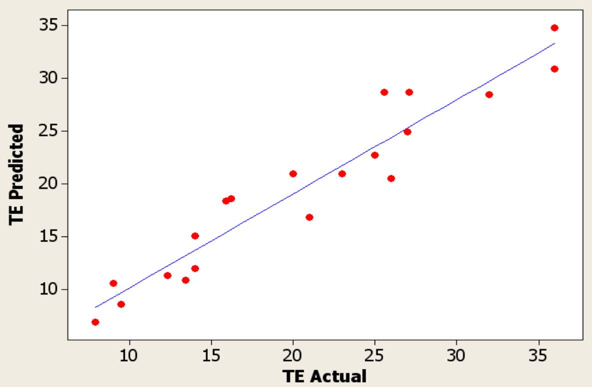

Figure 4: Comparisons of the ANN-predicted results and experimental (actual) results for brake thermal efficiency

3.1) Brake power

The predicted amounts of brake power for different fuel blends are shown in Figure (5). As the Figure shows there is no significant deference for brake power with change in biodiesel percentage in fuel mixture. However, the maximum brake power is for the fuel blend included 100% biodiesel at full engine load. Also the minimum brake power happens at 25% engine load for B0.

likewise, Song and Zhang[21]the brake power increases with increasing the amount of biodiesel (Figure (5)). Probably, could be due to the higher oxygen content of biodiesel in combustion region that provided more complete combustion. This means that biodiesel in the fuel mixture increases oxygen content of the blend; that causes higher combustion efficiency especially in higher loads and compensates the loss of heating value of biodiesel for these fuel blends [5, 22]. In addition the engine delivers fuel on volumetric basis and biodiesel density is higher than that of diesel, which supplies more biodiesel to compensate the lower heating value [23].

As shown in Figure (5) the brake power of the engine is relatively high at higher engine loads due to more opening of throttle and then increase in fuel consumption. Also because the increase in combustion temperature leads to more complete combustion during the higher load [24]. Also at higher engine load, a beneficial effect of biodiesel as an oxygenated fuel was seen to generate more complete combustion, which means increased brake power. This indicates that the addition of oxygenated fuel is most effective in rich combustions [2, 25].

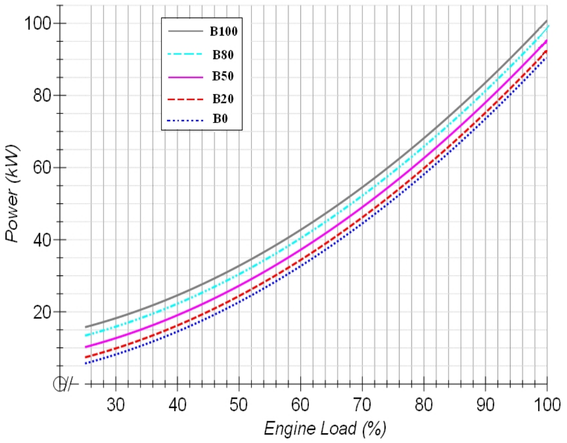

Figure 5: The predictions of the brake power values with respect to engine load for different fuel blends

3.2) Brake torque

Figure (6) shows the effects of biodiesel percentage and engine load on the brake torque of the engine at constant engine speed. As the figure shows the maximum brake torque is for the fuel blend included 100% biodiesel at full load. Also the minimum brake torque happens at 25% engine load for B0.

Similarly in the prediction of brake power, the values for the brake torque trends to increase by increasing biodiesel proportion in fuel mixture. These increases are understandable because of high lubricity and the higher oxygen content of biodiesel. These properties might result in the reduced friction loss and more complete combustion and thus especially improve the brake effective torque and compensates the loss of heating value of biodiesel[26].

Also Figure (6) shows the brake torque increases with increasing engine load, because the increase in combustion temperature leads to more complete combustion during the higher load [24].

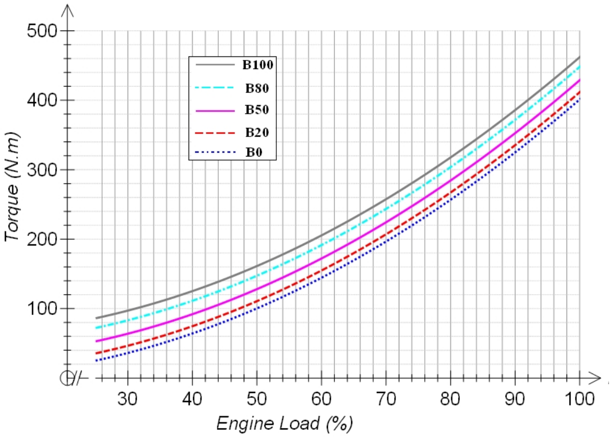

Figure 6: The predictions of the brake torque values with respect to engine load for different fuel blends

3.3) Brake specific fuel consumption

Figure (7) shows the predictions of the brake specific fuel consumption values with for different fuel blends at various engine loads. As the Figure shows the maximum brake specific fuel consumption is for the fuel blend B100 at 25% engine load. Also the minimum brake specific fuel consumption happens at full engine load for the fuel blends included 20% and 50% biodiesel.

The values for the brake specific fuel consumption increase with the increasing amount of biodiesel in the fuel blends B80 and B100. At the same time, for the same volume, more biodiesel fuel based on the mass flow was injected into the combustion chamber than diesel fuel No.2 due to its higher density. In addition to these parameters, viscosity, the atomization ratio and injection pressure should be considered since they have some effects on the BSFC [21, 22]. On the other hand, the BSFC of B20 and B50 is less than B0 because of the higher oxygen content of biodiesel that improves the brake power and compensates the loss of heating value of biodiesel [5, 26].

As the figure shows with increase in load, the BSFC of biodiesel decreases. One possible explanation for this trend could be due to the higher percentage of increase in brake power with load as compared to fuel consumption [2, 26-31].

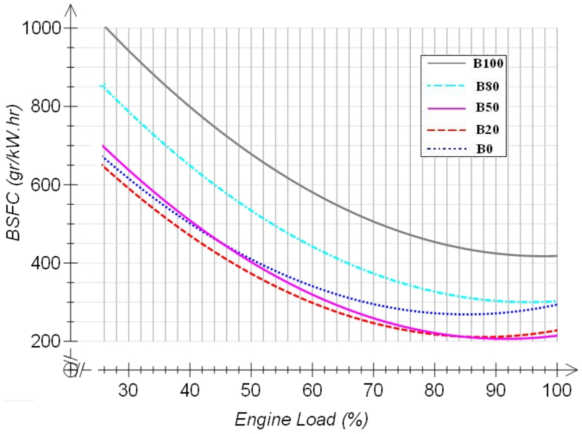

Figure 7: The predictions of the BSFC values with respect to engine load for different fuel blends

3.4) Brake thermal efficiency

Brake thermal efficiency of a diesel engine is the efficiency in which the chemical energy of a fuel is turned into useful work [32].

The predicted amount of brake thermal efficiencies (BTE) of the engine fuelled with diesel, B20, B50, B80 and B100 fuels are shown in Figure (8). B20 gives the best brake thermal efficiency of engine at full engine load. Also the minimum brake thermal efficiency happens for B100 at 25% engine load. The thermal efficiency has inverse relationship with the BSFC and lower heating value (H_{LHV}). Therefore, the primary reason for the decrease in the brake thermal efficiency of the fuel blends included 100% biodiesel than other blends is the higher BSFC in spite of lower energy content of biodiesels.

According to the Figure (8), it can be shown that the BTE of the engine is higher for B20 and B50 than that of B0. This improved efficiency was explained by some authors with more effective combustion and increased lubricity of these blends as compared to diesel fuel [5, 26]. In all cases, brake thermal efficiency has the tendency to increase with increase in applied load. This is due to the reduction in heat loss and increase in power developed with increase in load[26].

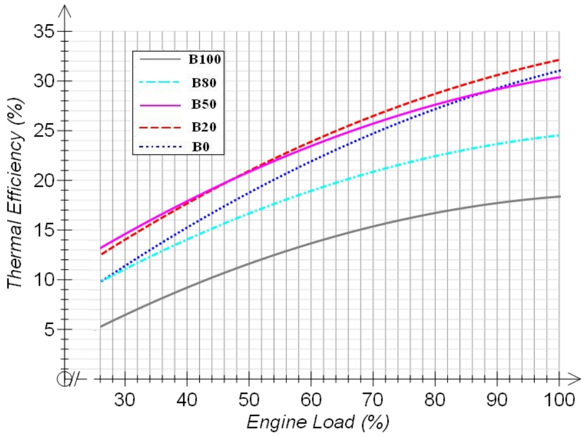

Figure 8: The predictions of the brake thermal efficiency values with respect to engine load for different fuel blends

4) Conclusion

1- Numerous ANN modeling implementations were carried out using different training algorithms of trainlm and trainscg at diversified number of neurons in the hidden layers.The best topology was 2 hidden layers (11-4); using Levenberg-Marquardt (LM) learning algorithm and tangent-sigmoid transfer function provided an efficient response to predict the output parameters.

2- The coefficient of determination (R^2) values equal to 0.97, 0.98, 0.97 and 0.96 were obtained for regression models for estimating of brake power, brake torque, BSFC and brake thermal efficiency respectively.

3- The results of this study show the usage of ANNs can predict the diesel power generator's performance parameters instead of having to undertake complex and time-consuming experimental studies. And also as the results showed the accuracy of regression models and artificial neural network have no difference to each other.

4- The brake power and brake torque increase with increasing the biodiesel percentage in fuel mixture due to higher oxygen content of biodiesel that improves the brake power and compensates the loss of heating value of biodiesel.

5- The brake power and brake torque level increases in higher engine load due to more opening of throttle and then increase in fuel consumption. Also the increase in combustion temperature leads to more complete combustion during the higher load.

6- The values for the BSFC increase with the increasing amount of biodiesel in the fuel blends B80 and B100 due to the lower heating value of biodiesel and more biodiesel that was injected into the combustion chamber than that of diesel fuel No.2. But The BSFC of B20 and B50 is less than B0 because of the higher oxygen content of biodiesel that improves the brake power and compensates the loss of heating value of biodiesel.

7- The brake thermal efficiency of the fuel blends included 80% and 100% biodiesel is lower than other blends is due to the higher BSFC in spite of lower energy content of biodiesel.

8- Between all of the fuel mixtures, B20 gives the best brake thermal efficiency of engine at full engine load.

9- The test results indicated that the fuel mixtures contained 20% and 50% biodiesel (particularly B20) in terms of performance characteristics could be recognized as the potential candidates to be certificated for usage in the diesel power generator.

10- As compared with other similar papers that using biodiesel-diesel fuel blends in diesel engines, the most of them agreed that, with biodiesel, engine power will drop. But in this study it was reported that there were surprising increases in power or torque of engine for pure biodiesel.

Acknowledgment

The authors would like to acknowledge Tarbiat Modares University (TMU) for the biofuel laboratory facilities to produce biodiesel of the research.

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پیش‌بینی مشخصه‌های عملکردی یک مولد قدرت دیزل بوسیله شبکه عصبی با کاربرد سوخت بیودیزل

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**نویسندهٔ مسئول*

چکیده

امروزه سوخت‌های جایگزین برای سوخت دیزل به شدت مورد بررسی قرار گرفته است. امروزه در ایران، دیزل ژنراتورها بطور عمده در کارخانه‌های مختلف صنعتی مورد استفاده قرار می گیرد. بهمین جهت، تخمین میزان عملکرد دیزل ژنراتورها با استفاده از زیست‌سوخت‌ها ضروری بنظر می‌رسد. برای اولین بار، در این مطالعه، پیش‌بینی مشخصه‌های عملکردی یک دیزل ژنراتور بوسیله روش شبکه‌های عصبی با کاربرد مخلوط‌های سوخت بیودیزل حاصل از روغن پسماند جهت تعیین این‌که چگونه ورودی‌ها بر خروجی‌ها تاثیر می‌گذارد، انجام شد. مخلوط‌های مختلف سوخت دیزل و بیودیزل جهت تعیین مشخصه‌های عملکردی موتور در دور ثابت و برای بارهای مختلف اعمالی مورد ارزیابی قرار گرفتند. در این تحقیق مدل‌های شبکه عصبی برای پیش‌بینی توان ترمزی، گشتاور ترمزی، مصرف سوخت ویژه ترمزی و بازده حرارتی ترمزی دیزل ژنراتور مورد نظر پیشنهاد شدند. ضریب تبیین بدست آمده برای همه مدل‌ها در این تحقیق بیشتر از ۰/۹۵ بود که این نشان می‌دهد که مدل‌های شبکه عصبی مصنوعی به عنوان یک ابزار قابل اطمینان برای پیش‌بینی مشخصه‌های عملکردی دیزل ژنراتورها محسوب می‌شوند.

اطلاعات مقاله

تاریخچهٔ مقاله:
دریافت: ۳ مرداد ۱۳۹۴
پذیرش: ۱۷ خرداد ۱۳۹۵

کلیدواژه‌ها:
شبکه عصبی
بیودیزل
مشخصه‌های عملکردی
دیزل ژنراتور
بار