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Use of Deep Learning Algorithms to Prevent Pantograph-Catenary Malfunctions

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Abstract

Today, the demand for rail transport is increasing. Studies in this area are increasing worldwide. While the railway infrastructure is increasing in the world, the suitability of the railroads and train sets built is of great importance in terms of road and passenger safety. The most important test to ensure road and passenger safety is on the electrification line. The energy required for the movement of the electric train is provided by the power line. Continuous contact between the power line and the pantograph is desired while in motion by providing continuous energy for the rail system to operate. Even short-term non-contact between the pantograph and the catenary adversely affects the rail system vehicle and the electronic systems inside. For this reason, the pantograph and catenary interaction should be controlled dynamically and statically in certain periods. In this study, dynamic and static control was provided by using deep learning. The k-fold cross-validation algorithm was used in the training and testing of the data sets. The data obtained is divided into 4 layers, each fold is divided into training and testing. Test and training results are given for each fold of the system. The data received from the system are recorded in CSV format. Using deep learning algorithms, failure points have been successfully detected up to 99.4%.

Key Words

"Catenary, data acquisition, high speed train, fault detection, pantograph"

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1. Introduction

The current demand for transportation is increasing. Studies in this field in our country have accelerated after 2007. Currently, it provides service on the Ankara-Konya and Ankara-Eskişehir lines, reaching a speed of 250 km/hour, and its duration is significantly shortened (Burrow et. al., 2004). Continues to railroad infrastructure in Turkey, compliance with the speed of the roads and train sets, and passenger road transport is of great importance.

The tests conducted to ensure road and passenger safety can be grouped under 3 main headings. The first of these is the controls on the electrification line. The energy required for the movement of the train comes from the power line. In order for the rail system vehicle to be continuously energized, the pantograph and a very short-term lack of contact between a continuous contact line and the pantograph do not adversely affect the bile rail system vehicle and the electronic systems inside. Therefore, test the pantograph and static statically periodically (Taşdan, 2015).

The second preferred method for road and passenger safety is to measure the rails on which the train set moves dynamically and statically. For this purpose, tests are carried out periodically to measure the road geometry and track profile. The third test is conducted to determine whether the passengers traveling in the rail system vehicle are traveling in the desired comfort. The general purpose of this test is to measure the interaction of the train set moving on the rail between the rail and the train and to detect the jolt felt by the passenger.

Electrically operated traction motors are required for the movement of electric rail system vehicles, and electronic cards operating with direct current for the control system (Erşin, 2015). Whether there is electrical continuity, which is vital for the movement of the electric train, should be checked periodically. Firms working in this field in our country have the technical capability to establish the railway infrastructure with their own means. However, in railways, it is not enough to just make the line, it is also necessary to test whether the line is in international standards and whether it is safe to travel at the high speeds reached. Currently, there is no state or private sector participant in our country that can measure and test on the 3 main tests mentioned above. The tests are made by companies from abroad, paying serious costs per km. Another importance of the tests for the train operator is that the errors on the line can be determined as a result of the measurement.

The tests required to perform the pantograph-catenary dynamic interaction can be grouped under 4 subtitles. The first of these is to measure the force exerted by the pantograph, which is mounted on the rail system vehicle and is responsible for providing the necessary energy to the train set. If this force is more than desired, the power line will break due to strain, and less will cause arcs during the journey and mechanical damage to the pantograph. The second parameter to be tested is that the force applied to the travel wire in a rail system vehicle with an unstable speed change in proportion to the speed of the train set. Acceleration at different speeds should also be measured and controlled. The third parameter to be measured is that the travel wire touching the pantograph does not create a heating effect on the coal on the pantograph and does not cause mechanical damage. In order to achieve this, it should be checked whether the travel cable is traveling within the allowed distance limits from one end to the other on the pantograph. This situation is expressed as a disability. The last parameter to be measured is to know where it is on the railway if there is a real problem in the interaction of catenary and pantograph. The Ankara-Eskişehir line is approximately 245 km. If a problem is detected and no information is given at which point on the railway, the test performed does not matter. Because, in case of failure, scanning the entire 245 km line will cause both time and cost loss.

Accelerometer sensor, load cell sensors and encoder or GPS system are required to perform the tests mentioned above (Kiessling, 2014). As a result of the regular application of the test and measurement systems to be detailed in the following sections on railways and rail system vehicles, both road and passenger safety and passenger comfort in trains that can reach high speeds will be carried out in accordance with international standards.

The aim of this study is to determine which tests are carried out on rail system vehicles, which parameters are paid attention to in the test result, and to make a real-time applicable test system whose results are analyzed.

High-speed trains are used safely in various cities of European and Asian countries today. In Japan, which has a significant weight in high-speed train lines, the density of passengers is also above the world average (Matvejevs, 2010). It serves over 305 million passengers a year with over 100 trains. High-speed trains were also used first in Japan. The first line was made between Tokyo-Osaka cities in 1959. Shinkansen, the line with the highest passenger density in the world, was opened in 1964. The line, which served approximately 30 million people when it was first commissioned, now serves more than 300 million passengers. Shinkansen is considered to be the line with the highest passenger carrying capacity in the world. Japan will continue to be one of the firsts in the field of high-speed rail. "Maglev", which moved without contact from the rail in 2003, reached a speed of 581 kilometers per hour and still maintains the record in this branch. In Table 1. the total railway line lengths of some countries are given.

Table 1. The total length of railway lines in the world and Turkey

Country	Total line length (km)
China	20.318
Japan	2.495
Spain	3.744
France	2.106
Germany	1.410
Italy	1.015
Russia	1.180
Turkey	1.048
Taiwan	345
South Korea	412
Belgium	209
Netherlands	120
United Kingdom	113
Swiss	107

2. Implementation Process for Pantograph-Catenary Faults

As in all areas, the biggest need for transportation is energy. Energy consumption is increasing day by day due to reasons such as requirements of modern life, increasing competition environment, cultural and social developments. The area where electric energy is used in transportation systems is Electric Rail Systems (ERS). Electric rail systems have been used in transportation for many years. The most important elements in ERS are pantograph and catenary. Compatibility between pantograph and catenary is one of the most important issues in these systems. A pantograph is mobile and a catenary is a fixed element. These two elements touch each other and move in ERS is provided. Therefore, having contact between them makes the system more complicated (Palta et. al, 2017; Cengiz et. al, 2018; Parlakyıldız et. al., 2020; Zhang et. al, 2018; Cengiz and Cengiz, 2018; Wu et. al, 2016; Akalp et. al, 2021; Kaynaklı et. al., 2018; Cengiz and Mamiş, 2017; Yaylak et. al., 2017; Eren et. al., 2017).

The current pantograph is the most important source of failure in Electrical Rail Systems. The pantograph is above the roof of the train and collects current from the overhead catenary line. The Catenary line is fixed to poles with support points at regular intervals along the railway line. When the train moves, the pantograph moves along the catenary line and delivers electrical energy to the ERS. The contact between the catenary and the pantograph should be optimal. When the ERS speed increases, vibrations occur in the catenary line. This disrupts the interaction between the pantograph and the catenary. These vibrations negatively affect the contact between the pantograph and the catenary. Since the contact between the pantograph and the catenary is interrupted in electrical contact, wear and arc occur. Rail systems are generally advantageous means of maintenance in terms of maintenance factors other than pantograph-catenary systems. So maintenance factor multipliers are high. Mechanical parts of ERS require very little maintenance for a long time.

When the studies in the literature were examined, the researchers either examined the catenary-pantograph interaction with the help of a simulation program or tried to measure the force applied by the pantograph to the catenary wire by creating a test system in the laboratory. However, none of the studies focused on the design and implementation of the real-time measurement system using these parameters and the information that the user will determine where the fault is on the railway by adding the localization information of the detected fault. Periodic movement of the catenary wire from one end to the other within the limits allowed on the pantograph is of great importance in terms of not being mechanically forced on the pantograph. In the studies in the literature, the determination of whether the catenary wire moves within the desired limits on the pantograph has not been mentioned much. However, with the help of the existing hardware on the system, it is possible to make this detection only by means of computer software without the need for any additional electronic sensor. The two conditions mentioned above are two elements that should be included in the measurement system, and when the project is completed, how these parameters are determined will be brought to the literature.

The advantages of electric railway vehicles over diesel-powered vehicles can be listed as follows:

- Noise and environmental pollution rate is much less than other vehicles.
- Low maintenance costs in electrical systems.
- As the motors act as generators in descents and braking, the catenary system is also energized.

- As the traction power is higher than other traction systems, the number of locomotives can be saved or it is possible to carry more load with the same power.
- Fuel savings are higher compared to other systems .

Ding examined the abrasive properties of the arc caused by not making proper contact on the carbon strip on the pantograph (Östlund et. al., 2008). It has found that arc wear and oxidation are effective on wear. It proved that the friction coefficient and wear rate are proportional to the current drawn from the catenary wire. In this study, he stated that the biggest factor in arc formation is low contact force, in other words, low friction. Thus, arc wear is seen as an important factor in shortening the life of the carbon on the pantograph arch.

Regarding the formation of arcs as a result of the pantograph-catenary interaction, Östlund examined this situation seasonally, and determined that the pantograph-catenary interaction decreases due to ice formation in winter, so that the arc is formed and has an erosive effect on the pantograph. It aimed to determine the contact strip wear by means of the direct current component occurring in the arc, and for this purpose, parameters such as current, voltage, train speed were used. The arc has a corrosive effect on the carbon on the arc, but considering that there are other factors that erode the carbon, it can be said that this study is incomplete in this sense. Midya et al. (2009) has worked on a system design that will examine the arc faults occurring in the system due to current and voltage values, therefore the current and voltage values at the moment the arc occurs (Midya et. al., 2009). Facchinetti et al., (2012) worked on a system in which the wear, arc and heating parameters were evaluated together in the complex system he developed.

Studies have been carried out using image processing techniques to find pantograph-catenary interactions and failures. The general purpose of these studies was to measure the top point of the rail system vehicle and the distance where the arch touches the catenary wire. In these studies Boguslavskii et al. (2006) used the Canny edge extraction algorithm. In addition to image processing studies, O'Donnel et al. (2006) conducted studies on real-time measurement of dislocation. Xiao-Heng et al. (2010) determined the abrasions on the carbon strip using edge extraction and detection algorithms in image processing techniques. Wang et al. (2013) made analyzes for wear using the contact pressure, train speed, and wear characteristic parameters. He has studied that mechanical and electrical wear are related to contact wire pressure. He stated that the contact wire will cause electrical wear due to contact with the pantograph with a lower pressure than desired, and high pressure contact will cause mechanical wear. Wang et al. (2013) stated that there is an inversely proportional relationship between speed and contact wire interaction, as the speed increases, the interaction with the contact wire decreases, and when the speed decreases, this interaction increases.

Bucca et al. (2009) developed laboratory tests on contact wire and pantograph made of different materials at different contact force, various current, and varying speed values. He gave the results of contact, graphy, and carbon in different current, velocity, and contact forces comparatively. The study in question is considered to be incomplete due to its material-based analysis of wear. Taran et al. (2013) created a two-mass model with a reference force of 100 Newtons for the pantograph. The model created is based on the simulation results of the catenary stiffness varying with time at different speeds, it has been understood that the model gives good results at constant speeds but does not give good results at variable speeds. Matvejevs (2010) continued their studies in a simulation environment because he thought that reducing the contact force effect would only be possible with special designs and that the special design to be made would be costly. Xiaodong et al. (2011) argued that abrasions are caused by vibration and that the control method to be applied to the pantograph-catenary system should be applied to the pantograph arch suspension to reduce these vibrations. Östlund (2008) concluded that the active control system to be implemented would be difficult to implement in practice and the system was not suitable for practice.

In the literature, there are experimental and simulation-based thesis studies conducted for the pantograph - catenary active control method. When these studies were examined, localization information was not given in any of the experimental studies for the real use of the application. Song et al. (2020) worked on cable irregularities in high speed trains in pantograph catenary interaction.

When the studies carried out until 2020 are examined, many models for the electrification interaction of rail systems have been proposed and field studies have been carried out. However, it has been observed in the studies that there is no work to locate the fault. The second point that was noticed in the reviews is that the test data obtained as a result of the test were not examined in advanced algorithms. In our field test, there are 9984 data and these data are interpreted in terms of deep learning algorithms. In previous studies, artificial neural network algorithms were not used in analyzing these data and making decisions for implementation. For this purpose, there are many new studies including different subjects (Cengiz et. al., 2017; Cengiz, 2020; Çıbuk et. al., 2020; Efe, 2018; Efe and Cebeci, 2013; Ertuğrul and Tağluk, 2017; Ertuğrul and Tağluk, 2016; Ertuğrul, 2018).

3. Test System Set Up To Collect Data

Four load cells capable of measuring up to four 500 Newton forces were used in the project. Since the project was carried out in UIC standards, the criteria determined by UIC were taken as basis in all operations and all equipment to be used, and it was determined that at least four load cells should be used according to these standards. When the train is in park position and the pantograph is in contact with the catenary, the minimum force applied by the panotgraph to the catenary is 70 Newtons. This minimum force is determined by applying the formula below. The forces acting on the pantograph are shown in equation 1. This calculation is also called pantograph balanced force. Contact force is seen in Figure 1.

$$F_c = F_b + F_a + F_I \qquad (1)$$

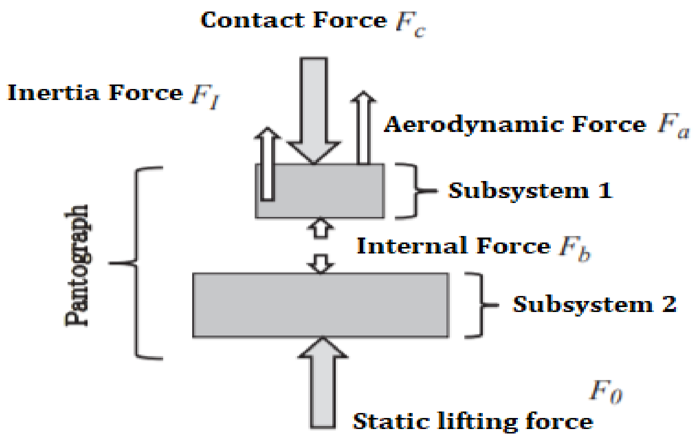

Figure 1. Contact force

If you want to measure the pantograph force in high oscillations, the forces calculated from different points of the pantograph are ideal. In this thesis, the acceleration from four points is measured.

$$\mathrm{FI} = \sum_{i=1}^{n} \mathrm{m.a,i} \tag{2}$$

Train contact force is calculated as in the following equation.

$$F_m = 0{,}00097.V^2 + 70\ N \tag{3}$$

As can be understood from Equation 3, the contact force applied when the train speed is zero should be 70 Newtons, the tests should be continued after this initial condition is met. Turkey in the current fastest operation speed of the train maximum rate per hour 250 km/h to the movement speed when this is thought to be an effect of 130 Newtons. While selecting the sensors, such calculations were taken into account, in terms of practical use, four sensors with a capacity of 500 Newton were used, and the total force was 2000 Newton, which is far above the capacity of the sensor to be used in the maximum speed train used in practice. As defined in the EN 50317 standard, the total force acting on the pantograph can be calculated by the following formula [26].

$$\mathrm{F} = \sum_{i=1}^{kf} \mathrm{Fsensor,i} + \frac{\mathrm{npeak}}{\mathrm{ka}}.\sum_{i=1}^{ka} \mathrm{asensor,i} + \mathrm{Fcorr,air} \tag{4}$$

The Figure 2 shows the test of the load cell with 2 kg.

Figure 2. Test of the load cell

The screen output of the software made is shown in Figure 3. This software is only for loadcell, software for all sensors was made separately and then combined.

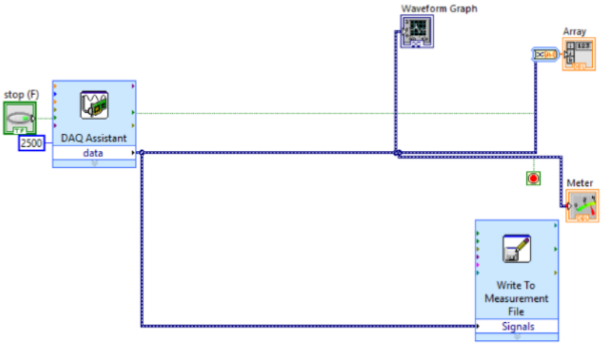

Figure 3. Software for retrieving loadcell data

Four accelerometers capable of measuring up to four 50 g acceleration were used in the project. Since the project was carried out in UIC standards, the criteria determined by UIC were taken as basis in all operations and all equipment to be used, and it was determined that at least four load cells should be used according to these standards. The selected accelerometer is uniaxial, and accelerometers are chosen to measure the vertical axis where the movements of the pantograph are only on the vertical axis. In the literature, this axis is called the z-axis. An example of the accelerometer sensor used in Figure 4 is shown.

Figure 4. An example of the accelerometer sensor used

GPS module is used for location information. The module has 12 channels and continuously detects high sensitivity GPS signals. GPS signal is detected at the antenna input of the module, position, speed and time information is transferred to the computer screen through the serial communication interface. Thanks to the module TTFF technology, it can detect low signal levels (Çıbuk and Cengiz, 2020; Cengiz, 2013). NMEA protocol is used. The GPS module with NMEA protocol is shown in Figure 5.

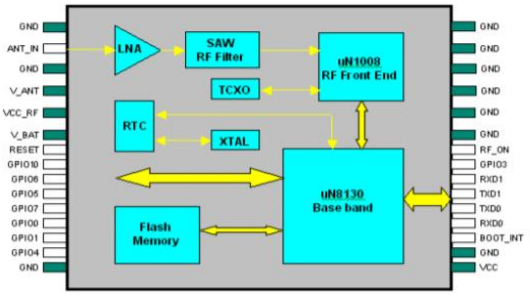

Figure 5. GPS module with NMEA protocol

With the software, the data are screen printed and recorded in real time. Used latitude, longitude, north/south information, east/west information, speed and angle data are displayed on the screen. Graphic software for receiving GPS data is shown in Figure 6. In Figure 7, the completed version of the project can be seen after the sensors are assembled. The system is ready to save data.

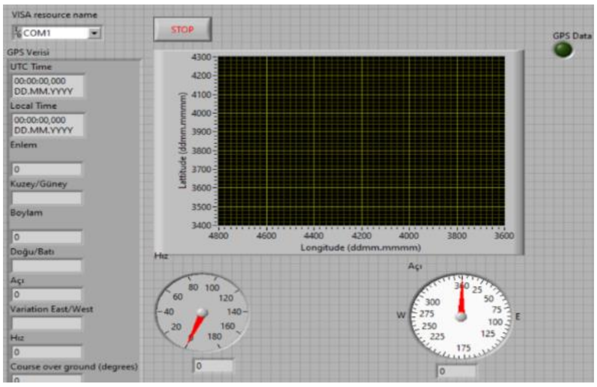

Figure 6. GPS gui software

Figure 7. Complete assembly

5. Method: Recommended Deep Learning Algorithm for Data Analysis

This study has two stages, in the first stage a measurement system was designed and implemented, and in the second stage, a deep learning algorithm was used to evaluate this density data. Deep learning is a learning method developed for learning, perception, and feature extraction applications, which consists of successive layers and examines the output data coming before each layer as input data. 768 * 11 sized data set is used. This method was chosen to evaluate the data obtained after the test, as the deep learning algorithms give fast results and offer a complete solution from the beginning to the end, not in parts. In this study, the force on which the catenary wire acts on the pantograph, affects the "F" parameter, ""Acc1", "Acc2", "Acc3", "Acc4", "Lcc1", "Lcc2", "Lcc3", "Lcc4" and "Vlc". Variables are modeled with the deep learning algorithm. Lcc data designed in the model are defined as (Newton) and F (Newton).

The 6-layer algorithm was created for the evaluation of the data set. Table 2 has been created for this model. The sequenceinput layer contains data consisting of 8 columns. There are 200 hidden units in the LSTM layer. While analyzing the data in the system, 8 folders were used, 4 of these folders were used for training and 4 for testing.

Tablo 2. Deep learning layers

1	'sequenceinput'	Sequence Input	Sequence input with 8 dimensions
2	'lstm'	LSTM	LSTM with 200 hidden units
3	'fc_1'	Fully Connected	50 fully connected layer
4	'dropout'	Dropout	50% dropout
5	'fc_2'	Fully Connected	1 fully connected layer
6	'regressionoutput'	Regression Output mean-squared-error with response	'Response'

Cross-validation is a statistical method used to estimate the skill of machine learning models. It is widely used in applied machine learning to select a model for a particular predictive modeling problem. It produces much more accurate results than other equivalent models. In this study, a k cross-validation algorithm was applied to estimate the skill of the machine learning model (Wang et al. 2013;Wu et.al, 2016;Parlakyıldız et. al., 2020;Michalski et. al., 1986;Carbonell, 1983;Parlakyıldız et. al., 2020;Parlakyıldız et. al., 2018). The k-fold cross-validation algorithm was used in the training and testing of the data sets. The data obtained is divided into 4 layers, each fold is divided into training and testing. Test and training results are given for each fold of the system. The results for the training data for cross-validation 1 are shown in Figure 8. The results for the test data for cross validation 1 are shown in Figure 9.

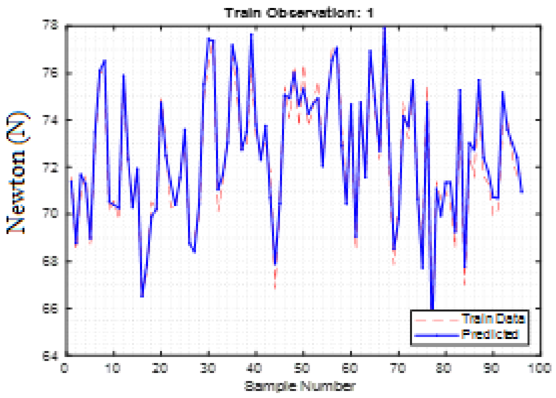

Figure 8. Fold-1 train data

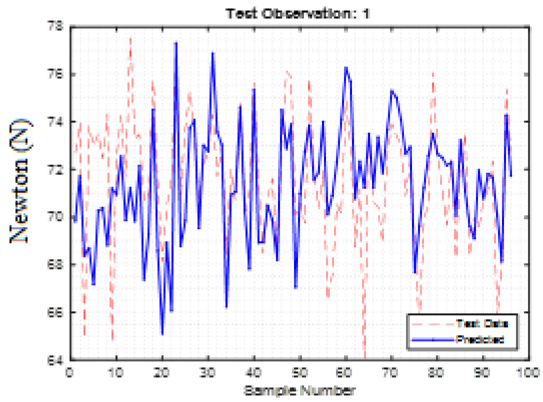

Figure 9. Fold-1 test data

The results for the training data for cross validation 2 are shown in Figure 10. The results for the test data for cross validation 2 are shown in Figure 11.

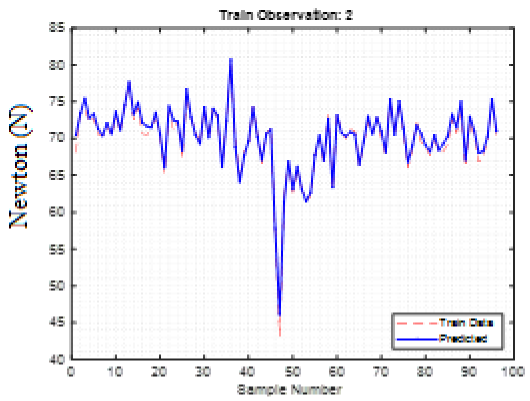

Figure 10. Fold-2 train data

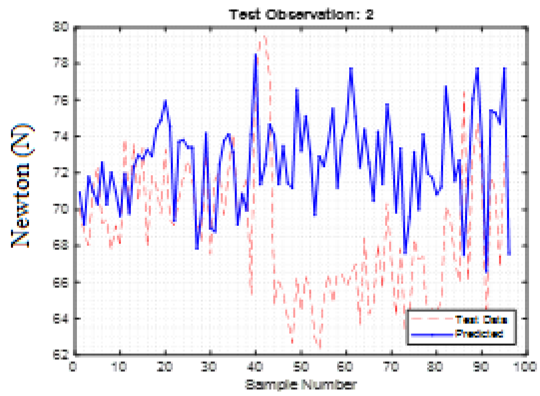

Figure 11. Fold-2 test data

The results for the train data for cross validation 3 are shown in Figure 12. The results for the test data for cross validation 3 are shown in Figure 13.

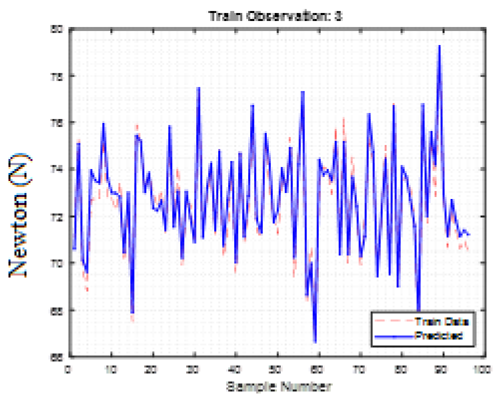

Figure 12. Fold-3 train data

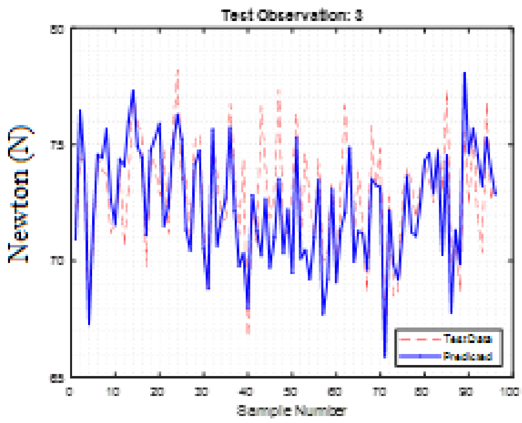

Figure 13. Fold-3 test data

The results for the train data for cross validation 4 are shown in Figure 14. The results for the test data for cross validation 4 are shown in Figure 15.

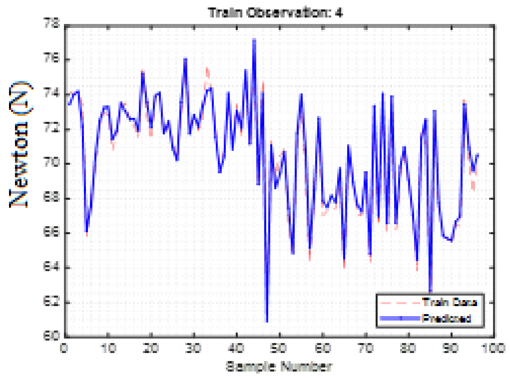

Figure 14. Fold-4 train data

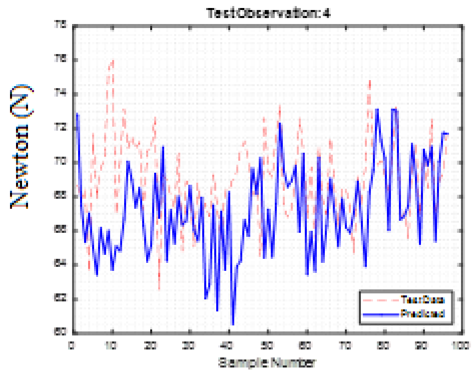

Figure 15. Fold-4 test data

MSE (Mean Square Error), RMSE (Root Mean Square Deviation), MAPE (Mean Percent Error), R2 (Determination coefficient) are used in the performance evaluation of the applied method. MSE is used to make sense of the performance of machine learning algorithms, it has a positive value and it can be said that its performance is better as it increases closer to zero. It is calculated as shown in Equation 5.

$$\text{MSE}=\frac{1}{\text{n}}\sum_{t=1}^{n} et^2 \qquad (5)$$

RMSE refers to the distance between real data and predicted data in machine learning algorithms. It indicates that it performs well as its value approaches zero, and a value equal to zero indicates that it did not make any mistakes. It is calculated as shown in Equation 6.

$$\text{RMSE}=\sqrt{\frac{1}{\text{n}}\sum_{t=1}^{n} et^2} \qquad (6)$$

MAE, in this method, the best line to the data is found, this is the average vertical distance between the position closest to the line at the perpendicular distance. Because it is easy to interpret, machine learning algorithms are often preferred in their results. Low-value results can be interpreted as the algorithm gives better results. It is calculated as shown in Equation 7.

$$\text{MAE}= \frac{1}{\text{n}}\sum_{t=1}^{n} \left|\frac{\text{et}}{\text{yt}}\right| \qquad (7)$$

MAPE performs its calculations provided that there is no zero between the values, the maximum value of the predictive value is 100, but the lower the value, the better the algorithm can be said. It is calculated as shown in Equation 8.

$$\text{MAPE}= \frac{\%100}{\text{n}}\sum_{t=1}^{n} \left|\frac{\text{et}}{\text{yt}}\right| \qquad (8)$$

The error performance results regarding training data for 4 folds in the models used are shown in the figure below. The fact that the results are below 1 proves the success of the applied algorithms. The error performance results regarding the test data for 4 folds in the models used are shown in the Figure 16. Average error value for each fold has shown below. The error performance results regarding the test data for 4 folds in the models used are shown in Fig. 17.

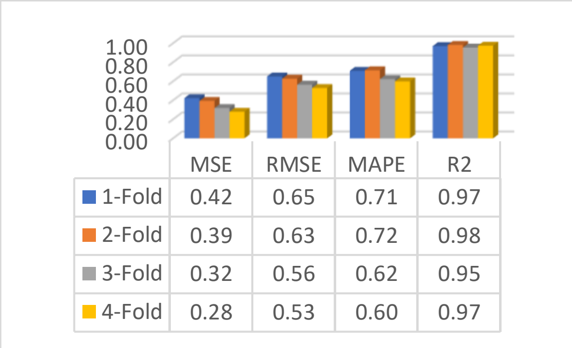

Figure 16. Learning performance of the system

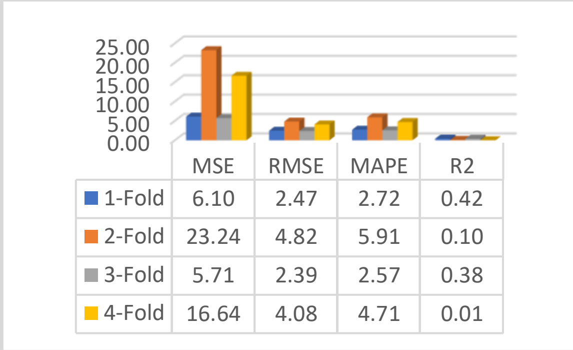

Figure 17. Test performance of the system

6. Conclusion

The main purpose of the pantograph and catenary in rail system vehicles that provide electricity with electricity in railway systems is to provide energy to the system and to keep the current collection capacity of this energy at an optimum level. The general name of this system is called pantograph - catenary interaction system, and one of the most important parameters is to keep the force applied by the pantograph to the catenary within the desired limits and to control whether it travels within certain limits in a way that does not cause mechanical problems to the pantograph while navigating on the pantograph.

When a new electric rail line is installed, the line needs to be certified in terms of measuring the reliability of the line, it is checked whether it is safe to travel on the line by checking it periodically on the certified line. Considering that the line installed will be 100 km or more while conducting all these tests, it is undoubted that hundreds of thousands of data will be recorded in the system when tests are made with the measurement system. Controlling these hundreds of thousands of data manually by an operator will cause both troubles and mistakes, and it is obvious that this mistake will cause serious financial damages for the line, rail system vehicle, train operator and passenger. These negative situations will cause serious financial losses as well as irreparable consequences such as loss of passenger life.

After the measurement process is carried out, the next important step is the examination and processing of the data received. In the systems currently used, measurement data are sent to the company that produces the test system, and a certain fee is paid and transactions are made according to the results from that company. It is possible for the local user to access the data recorded by the test company because the company saves these data in a format that their software can read. In this study, the measurement results are recorded in csv format that can be accessed by everyone. The next step after saving the data is to interpret them by an expert personnel or even to determine if there is a malfunction. For this purpose, deep learning algorithms have been used and the training results have been successfully tested up to 99.4%.

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