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KOHONEN NETWORK BASED FAULT DIAGNOSIS AND CONDITION MONITORING OF PRE-ENGAGED STARTER MOTORS

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ABSTRACT−In this study, fault diagnosis and monitoring of serial wound pre-engaged starter motors have been carried out. Starter motors are DC motors that enable internal combustion engine (ICE) to run. In case of breakdown of a starter motor, internal combustion engine can not be worked. Starter motors have vital importance on internal combustion engines. Kohonen network based fault diagnosis system is proposed for fault diagnosis and monitoring of starter motors. A graphical user interface (GUI) software has been developed by using Visual Basic 6.0 for fault diagnosis. Six faults, seen in starter motors, have been diagnosed successfully by using the developed fault diagnosis system. GUI software makes it possible to diagnose the faults in starter motors before they occur by keeping fault records of past occurrences.

KEY WORDS : Pre-engaged serial wound starter motor, Kohonen network, Fault diagnosis, Condition monitoring

1. INTRODUCTION

Manufacturers and users of electrical machines take measures to prevent motor faults. However, the faults inside of motors can be determined after a long time. The duties of electrical motors are getting more complex and are being used in places that have vital importance for people. Unexpected breakdown of these motors causes big losses. Unless fault diagnosis is done on time and measurements are taken before the faults are occurred, the replacement of machine is caused. For this reason, fault diagnosis before occurrence has got importance (Subhasis *et al.*, 1999; Vas, 1993). There are various fault diagnosis methods that include different scientific methods and technologies to determine the motor faults and diagnose them before faults occur (Subhasis *et al.*, 1999; Vas, 1993; Chow, 1997; Leonhardt *et al.*, 1997; Gao *et al.*, 2001).

Fault diagnosis is the process of followings: to detect the fault; to determine where the fault is occurred; and to determine the type and magnitude of the fault. Fault diagnosis system should be able to determine small sized faults and newly developed faults. This should also be determined when disturbance effects to a system is happened. Besides, to lessen the number of incorrect diagnoses, a diagnosis system should also have certain flexibility.

Small powered DC motors have wide application area (such as small house devices, military, automobiles, airplanes, etc.). As the importance of fault diagnosis and determination of DC motors and on-line monitoring and quality control increases, the interest of engineers and scientists for this area is also getting greater. Today, determination of faults in these motors is being done by experts using traditional techniques. These traditional techniques can not meet all demands and requests (Liu *et al.*, 2000). Studies on fault diagnosis and determination of DC motors are being carried out (Liu *et al.*, 2000; Moseler *et al.*, 2000; Füssel *et al.*, 2000; Hajiaghajani *et al.*, 2004).

Kohonen self organizing map (SOM) algorithm is being used in numerous engineering fields successfully. Some of them are: process and system analysis; fault determination; voice recognition; robotics (as robot navigation); statistical pattern recognition (Kohonen, 1996). The faults encountered in an energy transfer system have been determined and classified using artificial neural network. As artificial neural network, Kohonen network has been used. The voltage and current values of high voltage lines have been used as input information. Kohonen network has had 100% accuracy in diagnosis of faults encountered in high voltage lines (Chowdhury *et al.*, 1996).

Kohonen network is being used for fault diagnosis and harmonic analysis of electrical motors (Vas, 1999). Using Kohonen feature map network spectral data, fault diagnosis of induction motors has been carried out. For this motor, short circuit, unbalanced supply and broken

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*Corresponding author. e-mail: omerbay@gazi.edu.tr rotor bar faults have been diagnosed with 100% success (Murray *et al.*, 1997). Using Kohonen neural network faults have been diagnosed by using stator and rotor currents of a synchronous generator (Jiang *et al.*, 1993). By applying the Fast Fourier Transform (FFT) analysis of an induction motor vibration signal to Kohonen network fault diagnosis study has been carried out (Penman *et al.*, 1994). In induction motors, bearing faults have been diagnosed with SOM by using asymmetry of power supply, leakage flux measurement, spectral values of vibration and vibration signal (Tanaka *et al.*, 1995; Harris, 1993; Kowalski *et al.*, 2003; Hoffinan *et al.* 2002). By combining Kohonen network with methodology of other artificial neural network, fault diagnosis studies on electric motors are being carried out (Yang, 2004).

In this study, Kohonen network based fault diagnosis and condition monitoring system has been developed to diagnose the faults of starter motors, before faults are occurred. With the help of the proposed system, users are able to take measures before the faults are occurred and/ or before the faults get bigger. Kohonen neural network has been preferred, because learning is not necessary for it and it gives results fast. Because of these properties, Kohonen network is widely used in classification problems.

In the introduction of this article, information about studies on fault diagnosis and determination by using Kohonen network is given. In the second section, how to measure current and voltage signals of faulty starter motor and the results acquired from the measurements are presented. In the third section, information about Kohonen network is given. In the fourth section, the features of developed GUI fault diagnosis software and its usage is introduced. In the concluding section, the advantages and disadvantages of developed system are expressed and suggestions for future studies on this subject are presented.

2. MEASUREMENT OF CURRENT AND VOLTAGE SIGNALS OF STARTER MOTOR

Starter motors, convert electrical energy received from battery into mechanical rotational energy. Starter motor is an electrical motor that works under heavy duty. Starter motor transfers rotational energy to internal combustion engine flywheel with the help of a gear pinion. Rotational moment of starter motor is requested to be high in order to enable internal combustion engine start to rotate. In first movement, starting initial moment of serial wound DC motor is high. Because of this characteristic, serial wound DC motors and their different connection types are preferred to be used as starter motor (Bolenz, 1995).

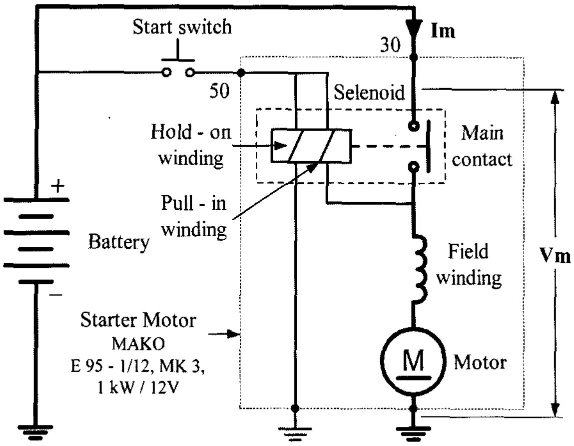


Figure 1. Simple starter system scheme of a vehicle.

In this study, fault diagnosis of starter motor that starts internal combustion engine has been carried out. Starter motor current (Im) and voltage across motor (Vm) (shown in Figure 1) has been measured and then faults are diagnosed by applying them to Kohonen network. Vm is summation of voltages across field winding and armature. Im is the current flows through field winding and armature. Pull-in winding current flows over motor. The value of this current is very small.

Because starter motors draw high current while working, wire between motor and battery should be short and thickness of wire should be chosen according to current to be carried. Resistance of current carrying wire should be as small as possible. The maximum resistance of this wire should be 2, 5 mΩ and voltage over this wire should not exceed 0, 5 V. Electrical connection of high current carrying wire with starter motor is performed with a solenoid switch. Voltage of solenoid switch is provided from start switch (Denton, 2000).

Performance graph of motor used for fault diagnosis is given in Figure 2. In figure, graphs of revolution (N),

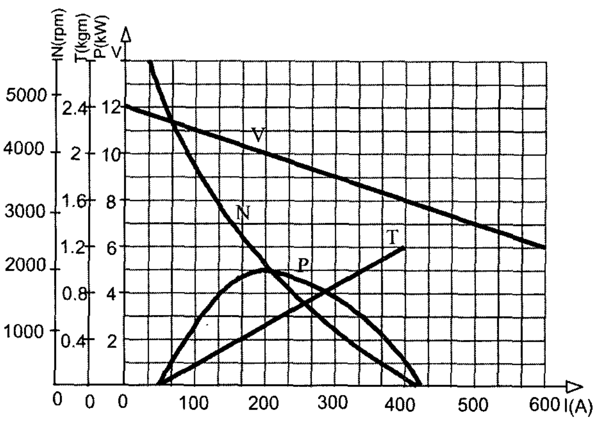


Figure 2. Performance graph of a starter motor (MAKO E 95-1/12-MK 3, 1 kW/12 V).

power (P), torque (T) and voltage (V) in respect to current are drawn respectively. This information about starter motor gives us reliable information about the condition of the motor. If these values are different from the expected values, it means that there are some faults occurred or about to occur. When putting the faults on I/V graph, performance graph has also been benefited.

The torque of an internal combustion engine, in which the starter motor is used with, changes according to the inadequate level of lubricating oil or existence of lubricating problems or coldness of weather etc. Because of this internal combustion engine, an alternating and variable load is created in front of starter motors. Besides, the number of revolution in serial wound DC motors change depending on the load. This causes the errors due to problem in load although the starter motor is in good condition. Therefore ICE has not been allowed to work, during measurements of voltage and current signals. To measure signals of faulty starter motors, measurement rig shown in Figure 3 has been prepared.

The current signal of starter motor is measured by a clamp type current sensor. While measuring voltages, measurement probe of Pico ADC-212 has been directly connected. Pico ADC 212 has 2 input channels and 12 bits resolution. It's accuracy in measurement is ±1% and sampling rate is 3MS/s. Besides, having 32 K data memory makes it possible to be used in measurements of more complex signals.

Faults occurred in starter motors are not only caused by starter motors. Other components and materials may also cause faults. For example, weakness of battery, looseness of battery poles, broken connection cables etc.

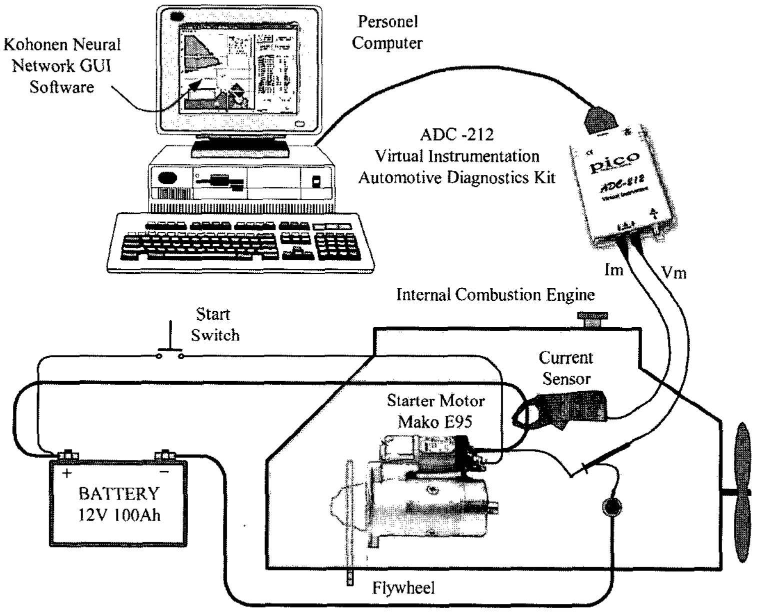
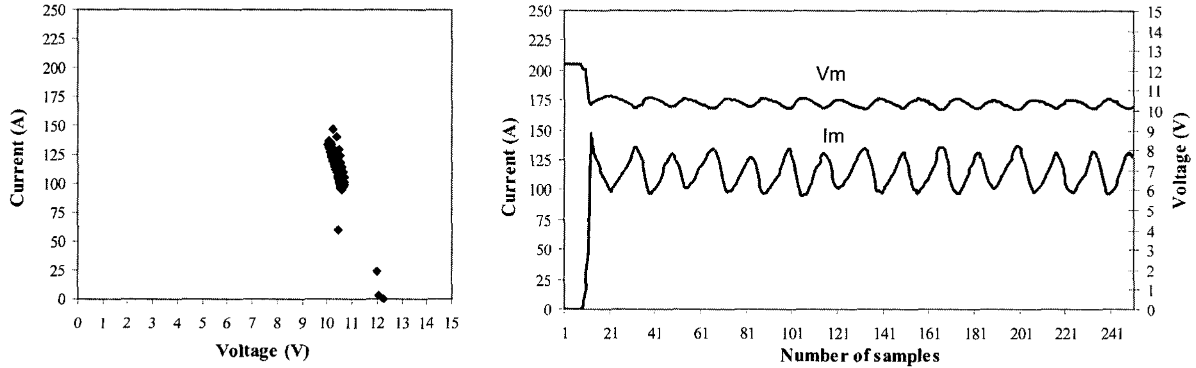
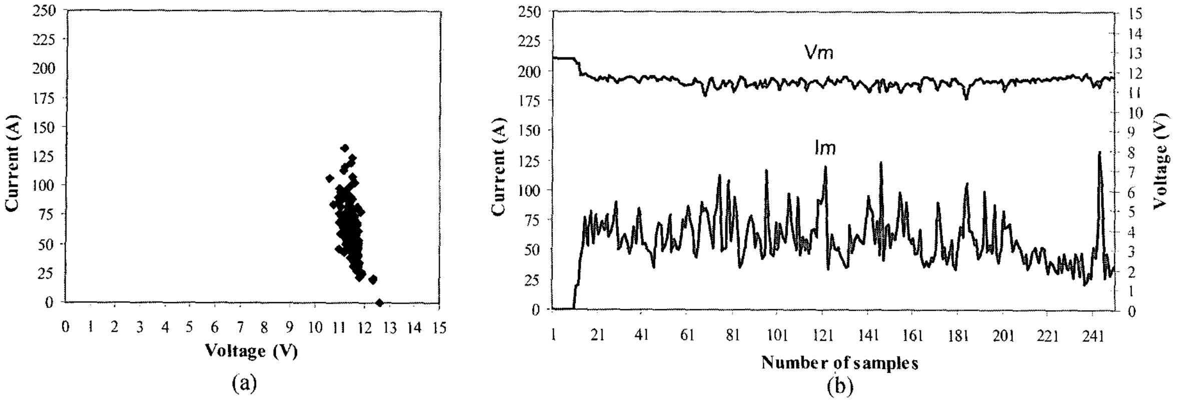


Figure 3. Measurement rig of current and voltage signals of a starter motor.



(a) (b)

Figure 4. Healthy starter motor: (a) Vm/Im graph; (b) Voltage and current of the the starter motor.



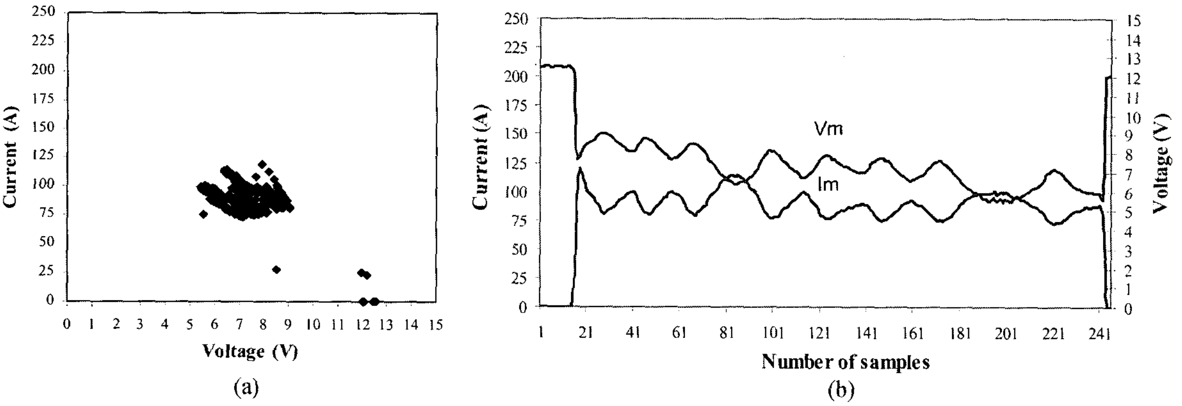
(a) (b)

Figure 5. Brush fault: (a) Vm/Im graph; (b) Voltage and current of the the starter motor.

In the current drawn and voltage of a healty starter motor, a small peak is observed for pistons of four cylinder internal combustion engine (Figure 4(b)).

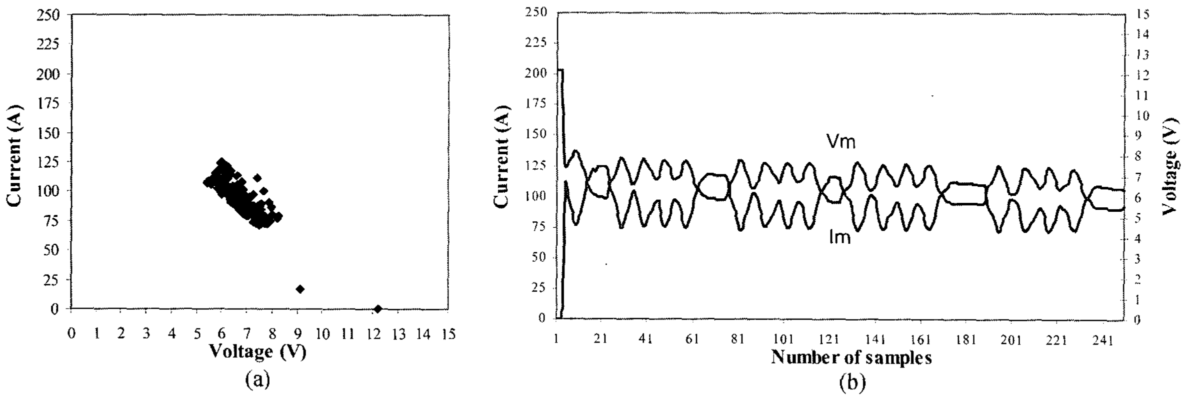
Brush fault is defined as followings, uneven contact of brush, dirty collector or brush, inadequate adjustment of springs that provide brush press, oval shape of collector and end of brushes lives. In those cases, movements of pistons can not be observed and sparks are created between brushes and commutator of the starter motor. Sometimes, when brushes are not in contact, starter motor stops (Figure 5(b)).

Connection fault is the case of followings; decrease in



(a) (b)

Figure 6. Connection fault: (a) Vm/Im graph; (b) Voltage and current of the starter motor.



(a) (b)

Figure 7. Battery fault: (a) Vm/Im graph; (b) Voltage and current of the starter motor.

crosscut of connection cable, loose in cable connection or loose in battery pole connections. Decrease in crosscut of cable in a certain area cause increase in current, but if this decrease is much then it affects current of starter motor. In loose connections, in result of increase in contact resistance starter motor current is decreased (Figure 6(b)).

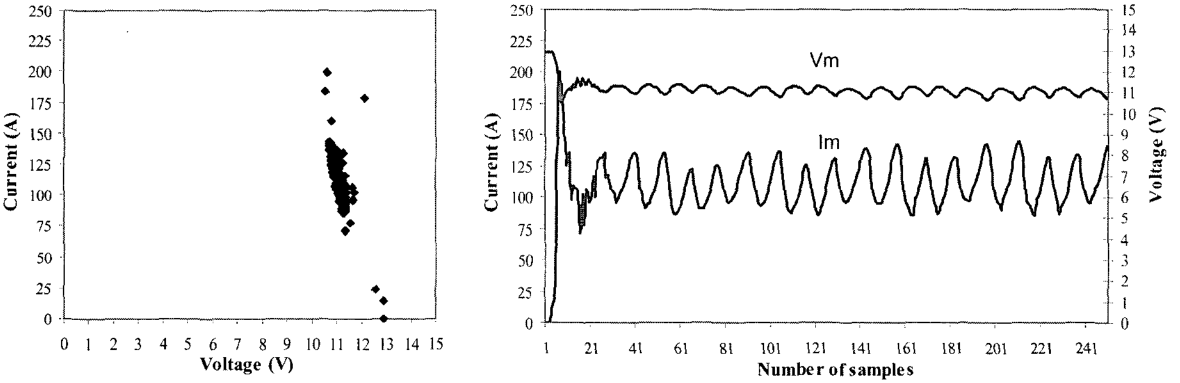
If battery is faulty, battery can not supply the current necessary for the starter motor to rotate the crankshaft. For this reason, space between two aks is rather long. Voltage across the motor falls down to 7–8 V. Because of insufficiency of battery, dead times are occur in upper points of voltage and current signals. In these cases, starter motor is about to stop (Figure 7(b)).

Armature fault is classified as follows; short circuit of armature windings, breakdown of armature bearing and open circuit in armature windings. In case of short circuit in armature windings, the current drawn is increase. Spoiling on peaks caused by piston movements and decrements in periods is observed (Figure 8(b)). Starter motor starts working with strokes. When Armature windings are short circuited, although starter motor seems working normally, piston movements isn't observed in signals. At the time of pressing the starter, if brush contacts that winding, starter motor doesn't work. In measured signals, voltage and current drawn by pull-in winding of solenoid is observed.

In field winding faults, short circuit to ground and short circuit to windings of itself are investigated. In case of short circuit in windings, starter motor rotates, but since the magnetic field is not created thoroughly, alternations are occur (Figure 9(b)). Depending on magnitude of short circuits of field windings to ground, motor draws excessive current. Since sufficient magnetic field is not created motor doesn't rotate. This is the short circuit fault. In Figure 10(b), as short circuit fault, the case of short circuit of field windings to ground is shown.

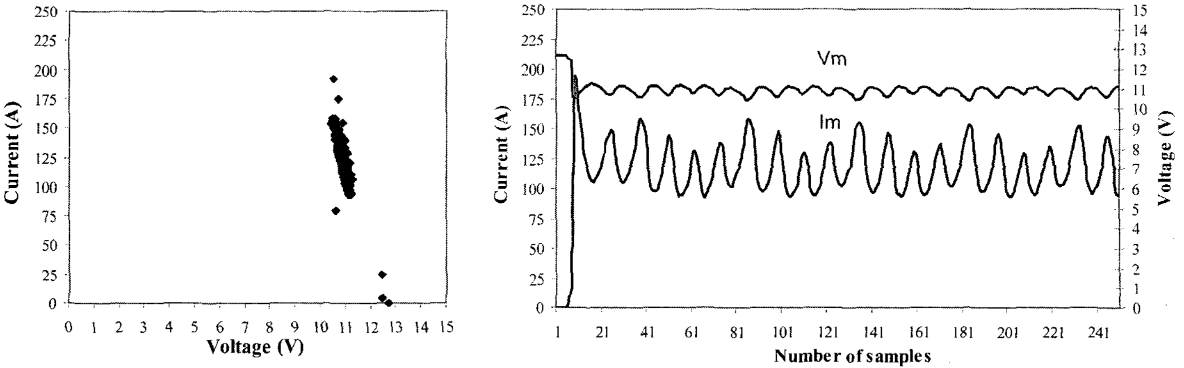
3. KOHONEN NEURAL NETWORK

Kohonen neural network in other words self organizing map is an unsupervised training network. This network structure has been developed by Teuve Kohonen (Kohonen, 2001). Kohonen neural network has two



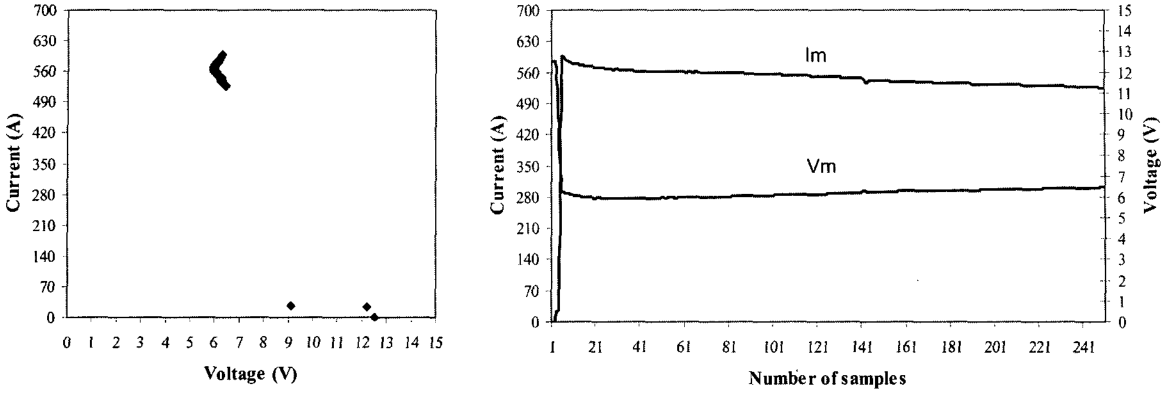
(a) (b)

Figure 8. Armature fault: (a) Vm/Im graph; (b) Voltage and current of the starter motor.



(a) (b)

Figure 9. Field winding fault: (a) Vm/Im graph; (b) Voltage and current of the starter motor.



(a) (b)

Figure 10. Short circuit fault: (a) Vm/Im graph; (b) Voltage and current of the starter motor.

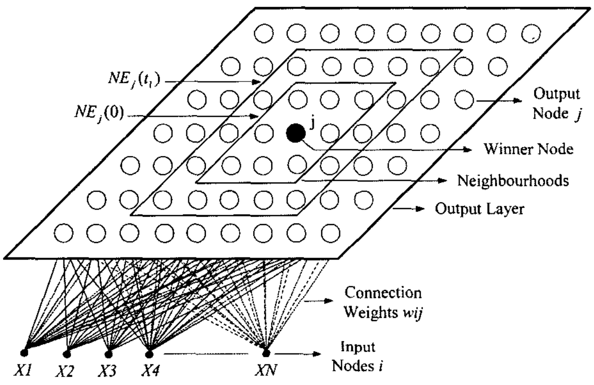


Figure 11. Kohonen network structure.

layers as input and output (Figure 11). Neural nodes in output layer are linked with each other and with neural nodes in input layer. When network is worked, random weights are assigned. Network starts performing when input information is applied. After training one neural node wins. Weights of neural nodes in the border that shows the neighborhoods of the neuron are changed. In result, network indicates a region that includes neural group. Kohonen network is separated as one dimensioned and two dimensioned (Haykin, 1999).

Kohonen neural network algorithm is given as follows. Having less number of layer and arithmetical easiness of network increases speed of network (Lippmann, 1987). Before executing network algorithm, number of neighborhood NE_j and η gain term (learning speed) constants values must be assigned.

(1) Determination of weights
Small random values are assigned for connections among N input and M output nodes.

(2) Input is applied to network.

(3) Distance among all nodes is calculated.
Distance between input and an output node (j), di, is calculated by the formula in Equation (1).

$$d_i = \sum_{i=0}^{N-1} (x_i(t) - w_{ij}(t))^2 \qquad (1)$$

In this formula, xi (t) is the i th input node, t is time and wij (t) is weight value at the t th time between the i th input node and j th output node.

(4) Output node that has the smallest distance is selected.
Selected j* output node is the node that has the smallest distance value, di.

(5) The weights of j* node and its neighbors are renewed.
NE_j (t) weights of j* node and its neighboring nodes are renewed with the formula in Equation (2).

$$w_{ij}(t+1) = w_{ij}(t) + \eta(t)(x_i(t) - w_{ij}(t)) \qquad (2)$$

$$j \in NE_j(t) \qquad 0 \le i \le N-1$$

Where, η(t) is the gain term. This value (0 < η(t) < 1) decreases with time.

(6) Going back to second step process is repeated (Lippmann, 1987).
Kohonen network is generally used in classification. Classification ability of input vectors and training ability of input vector distribution of these networks is very high. Neural elements indicate vectors scattered on a plane. Neural nodes in SOM network calculate their values according to discriminate function. This discriminate function forms the basis of competitive among neural nodes. Winner neural node determines the neural nodes around it topographically. Thus, cooperation with neighboring neural nodes is provided. The values of these

determined neighboring nodes are increased in relation with input values according to discriminate function. Besides, connection weights of these neural nodes are adjusted to a convenient value (Haykin, 1999; Fausett, 1994). They work in principle of winning of race and having 1 value for winner element, having 0 values for others.

4. KOHONEN NETWORK BASED FAULT DIAGNOSIS AND CONDITION MONITORING GUI SOFTWARE

In this study, Kohonen network with two dimensions has been used. Current and voltage of the starter motor are applied to as input signals. Each fault area is placed on I/V graph as seen in Figure 12. This placement operation is done by expert opinion and benefited from performance graph of starter motor. The volt axis begins from 5 V. When battery voltage falls down below this value the starter motor doesn't work. With the professional experiences of expert people and with the help of performance graph, regions of faults are marked on I/V graph.

In main menu of developed GUI software, parameters of Kohonen network can be seen. These parameters can be changed by user. The signals to be applied to the input of the network can be taken either on-line or off-line. In off-line working, the data from the file that saved before are applied to Kohonen network. In on-line working, data are applied to network as real time with the help of Pico ADC-212. After measuring of signals, the network is run. Since the current and voltage value of each signal is different, each signal is placed on I/V graph in different pattern. Kohonen network finds the value of winner node and then marks it with a circle. If this winner node corresponds to the determined range, the check box of that fault from the fault list is marked by the software, thus, the condition of starter motor is indicated to user.

The test rig of the proposed fault diagnosis system is shown in Figure 13. In on-line reading mode, the first thing to be done for measuring the signals of starter

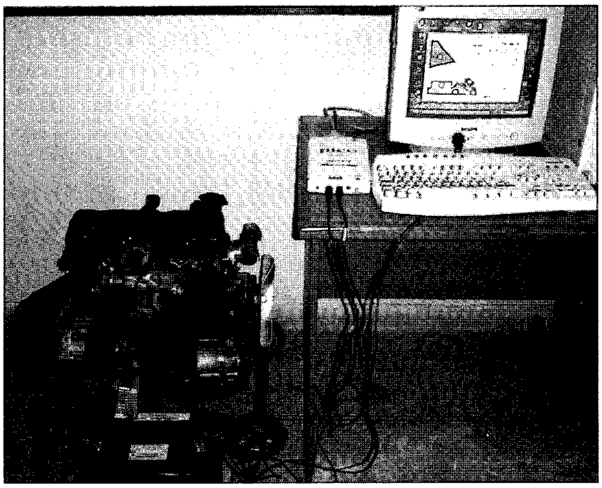
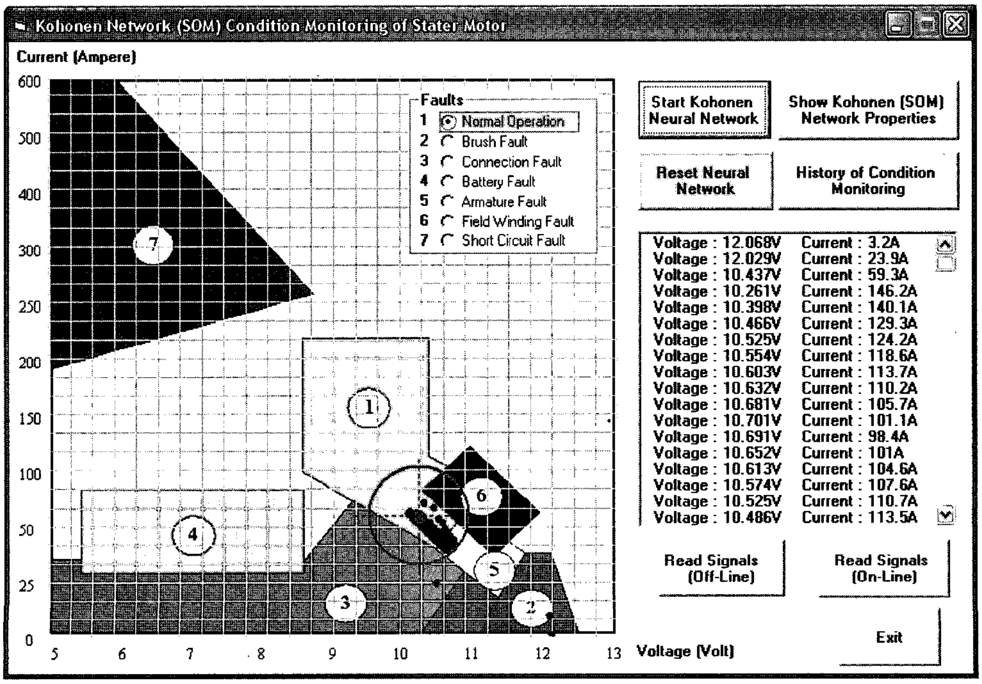


Figure 13. Test rig of the proposed system.



Faults
1 ● Normal Operation
2 ○ Brush Fault
3 ○ Connection Fault
4 ○ Battery Fault
5 ○ Armature Fault
6 ○ Field Winding Fault
7 ○ Short Circuit Fault

```
Voltage : 12.068V   Current : 3.2A
Voltage : 12.029V   Current : 23.9A
Voltage : 10.437V   Current : 59.3A
Voltage : 10.261V   Current : 146.2A
Voltage : 10.398V   Current : 140.1A
Voltage : 10.466V   Current : 129.3A
Voltage : 10.525V   Current : 124.2A
Voltage : 10.554V   Current : 118.6A
Voltage : 10.603V   Current : 113.7A
Voltage : 10.632V   Current : 110.2A
Voltage : 10.681V   Current : 105.7A
Voltage : 10.701V   Current : 101.1A
Voltage : 10.691V   Current : 98.4A
Voltage : 10.652V   Current : 101A
Voltage : 10.613V   Current : 104.6A
Voltage : 10.574V   Current : 107.6A
Voltage : 10.525V   Current : 110.7A
Voltage : 10.486V   Current : 113.5A
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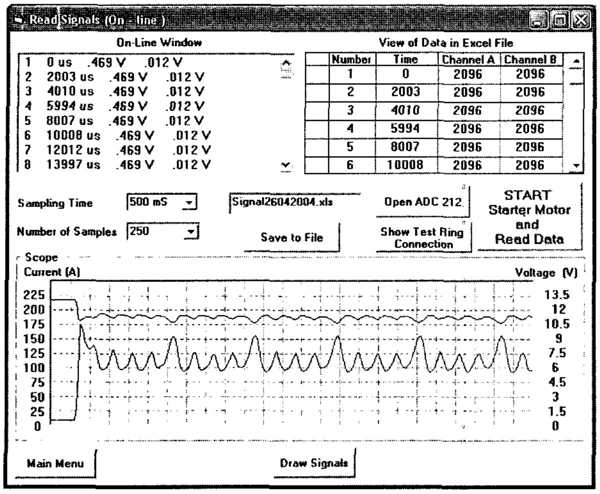
Figure 12. Main menu of the Kohonen network GUI software.

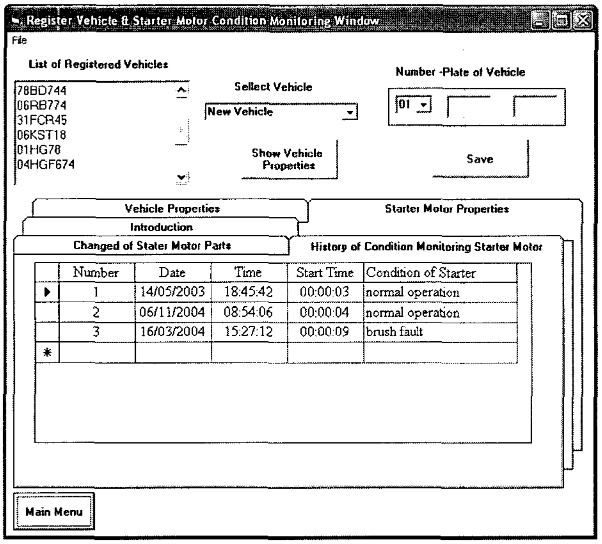


```
1   0 us      .469 V   .012 V
2   2003 us   .469 V   .012 V
3   4010 us   .469 V   .012 V
4   5994 us   .469 V   .012 V
5   8007 us   .469 V   .012 V
6   10008 us  .469 V   .012 V
7   12012 us  .469 V   .012 V
8   13997 us  .469 V   .012 V
```

Number	Time	Channel A	Channel B
1	0	2096	2096
2	2003	2096	2096
3	4010	2096	2096
4	5994	2096	2096
5	8007	2096	2096
6	10008	2096	2096

Sampling Time 500 mS
Number of Samples 250
Signal26042004.xls

Figure 14. On-line signal reading menu.



78BD744
06RB774
31FCR45
06KST18
01HG78
04HGF674

Sellect Vehicle: New Vehicle
Number -Plate of Vehicle: 01

	Number	Date	Time	Start Time	Condition of Starter
▶	1	14/05/2003	18:45:42	00:00:03	normal operation
	2	06/11/2004	08:54:06	00:00:04	normal operation
	3	16/03/2004	15:27:12	00:00:09	brush fault
*					

Figure 15. Condition monitoring of the starter motor window.

motor is to perform the connections of measurement tips. By pressing show test rig connection button, electrical connection scheme can be seen. After making electrical connections, by pressing Open ADC-212 button, Pico ADC-212 is got ready for measurement. User may change sampling time and number of samples to be taken before the measurement. By pressing start starter motor and read data button, starter motor is worked. Current and voltage signals are measured. Data which is read can be drawn in scope window (Shown in Figure 14). At the same time, these values are taken into an array in the software program. If these values are needed to be used later, it can be saved into a *.xls file.

Condition monitoring window of a starter motor is given in Figure 15. In starter motor condition monitoring, specifications of the starter motor, whether it has changed parts or not and fault diagnosis made before, can be seen. The system creates a *.mdb file for each vehicle. Personal information about owner of vehicle and specifications of the vehicle are entered to the software. Vehicles in the system are recorded with respect to its license tag. User can also record a new vehicle. In condition monitoring of a starter motor, date, time, and how long the starter motor is worked and results of Kohonen network are also recorded to the file of the vehicle

5. CONCLUSION

In this study, fault diagnosis and condition monitoring of starter motors were performed by using Kohonen network. In today, traditional methods have been used to find out the faults of starter motors. These traditional methods do not meet all the needs and demands. In proposed system, six faults observed in starter motors (brush fault, battery fault, open circuit fault, armature fault, field winding fault and short circuit fault) have successfully diagnosed. These faults have been classified by Kohonen network. Classification results and starter motor records are recorded backwards. When the condition of starter motor deteriorates, the proposed system can detect it. This means that, starter motor faults can be diagnosed beforehand.

To prove the validity of the proposed method and program, the system was tested using 50 sample data shown in Table 1. It has made 86% correct classification. The reason of having 14% faulty results is that, some faults symptoms similar to each other (such as battery fault and connection fault) and the starter motor currents can be different in winter and summer. These faulty results result from the signal applied to input of the network not from the structure of network. As the temperature of environment decreases, the torque of starter motor decreases required minimum speed of internal combustion engine to crank and current of starter motor increase. Changes in working condition change the current drawn by starter motor and this causes faulty diagnosis. To avoid this, I/V graph should be updated according to seasons or temperature.

In Kohonen network, since initial weight values are assigned random values, although the signal applied to input of the network is the same, winner node is different. Although this change amount is quite small, if the condition of the motor is in between two fault region, faulty diagnosis is carried out. To prevent this, in software program, first assigned values of random weights assigned to network is made constant and these values are used in all studies. Proposed system can be used fault

Table 1. Experimental results.

Faults & State	Number of samples	Number of correct classifications	Number of wrong classifications	Results of wrong classifications
Normal	10	10	-	-
Brush fault	5	5	-	-
Connection fault	7	6	1	Battery fault
Battery fault	8	6	1	Normal
			1	Connection fault
Armature fault	8	7	1	Normal
Field winding fault	4	3	1	Short circuit fault
Short circuit fault	6	6	-	-
Unknown signals	2	-	2	Undefined
Total	50	43	7	
Percentage (%)	100%	86%	14%	

diagnosis of starter motor in quality control workshop of manufacturers and in repairing shop. Developed GUI software allows user to change network parameters. This feature gains the software program flexibility and makes it possible to have better fault diagnosis results.

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REFERENCES

Bolenz, K. (1995). *Automotive Electric/Electronic Systems.* Robert Bosch GmbH. Stuttgart. Germany. 346–375.

Chow, M. Y. (1997). *Methodologies of Using Neural Network and Fuzzy Logic Technologies for Motor Incipient Fault Detection.* World Scientific Pub.. Singapore.

Chowdhury, B. H. and Kunyu, W. (1996). Fault classification using Kohonen feature mapping. *Intelligent Systems Applications to Power Systems. Proc. ISAP '96., Int. Conference on,* 194–198.

Denton, T. (2000). *Automobile Electrical and Electronic System.* 2nd Ed.. Arnold Pub.. Printed in Great Britain. 134–152.

Fausett, L. (1994). *Fundametals of Neural Networks,* Prentice-Hall, Inc.. USA.

Fuessel, D. and Isermann, R. (2000). Hierarchical Motor Diagnosis Utilizing Structural Knowledge and a Self-Learning Neuro-Fuzzy Scheme. *IEEE Trans. Ind. Elec.* **47**, **5**, 1070–1077.

Gao, X. Z. and Ovazska, S. J. (2001). Soft Computing Methods in Motor Fault Diagnosis. *Applied Soft Comp.*, **1**, 73–81.

Hajiaghajani, M., Toliyat, H. A. and Panahi, I. M. S. (2004). Advanced fault diagnosis of a DC motor. *IEEE Trans. Energy Conv.* **19**, **1**, 60–65.

Harris, T. (1993). A Kohonen S.O.M. based, machine health monitoring system which enables diagnosis of faults not seen in the training set. *Neural Networks, IJCNN '93-Nagoya. Proc. 1993 Int. Joint Conf.*, **1**, 947–950.

Haykin, S. (1999). *Neural Networks: a Comprehensive Foundation.* Prentice-Hall, Inc.. USA.

Hoffman, A. J. and van der Merwe, N. T. (2002). The application of neural networks to vibrational diagnostics for multiple fault conditions. *Computer Standards & Interfaces* **24**, **2**, 139–149.

Jiang, H. and Penman, J. (1993). Using Kohonen feature maps to monitor the condition of synchronous generators. *Neural Network App. Tools*, 89–94.

Kohonen, T., Oja, E., Simula, O., Visa, A. and Kangas, J. (1996). Engineering applications of the self-organizing map. *Proc. IEEE* **84**, **10**, 1358–1384.

Kohonen, T. (2001). *Self-Organizing Map.* Springer Verlag; 3th Ed.. Berlin. Germany.

Kowalski, C. T. and Orlowska-Kowalska, T. (2003). Neural networks application for induction motor faults diagnosis. *Mathematics and Computers in Simulation* **63**, **3-5**, 435–448.

Leonhardt, S. and Ayoubi, M. (1997). Methods of fault diagnosis. *Control Eng. Practice* **5**, **5**, 683–692.

Lippmann, R. P. (1987). An introduction to computing with neural nets. *IEEE ASSP Magazine*, 4–22.

Liu, X. Q., Zhang, H. Y., Liu, J. and Yang, J. (2000). Fault detection and diagnosis of permanent-magnet DC motor based on parameter estimation and neural network. *IEEE Trans. Industrial Electronics* **47**, **5**, 1021–1030.

Moseler, O. and Isermann, R. (2000). Application of model-based fault detection to a brushless DC motor. *IEEE Trans.Ind. Elect.* **47**, **5**, 1015–1020.

Murray, A. and Penman, J. (1997). Extracting useful higher order features for condition monitoring using artificial neural Networks. *IEEE Trans. Signal Processing* **45**, **11**, 2821–2828.

Penman, J. and Yin, C. M. (1994). Feasibility of using unsupervised learning, artificial neural networks for the condition monitoring of electrical machines. Electric Power Applications. *IEE Proc.* **141**, **6**, 317–322.

Subhasis, N. and Toliyat, H. A. (1999). Condition monitoring and fault diagnosis of electrical machines - a Review. *in Proc. Industry App. Conf. 34th IAS Annual Meeting*, **1**, 197–204.

Tanaka, M., Sakawa, M., Shiromaru, I. and Matsumoto, T. (1995). Application of Kohonen's self-organizing network to the diagnosis system for rotating machinery. Man and Cyber., *Intelligent Sys. 21st Century, IEEE Int. Conf.*, **5**, 4039–4044.

Vas, P. (1993). *Parameter Estimation, Condition Monitoring and Diagnosis of Electrical Machines*. New York. Clarendon Press. Oxford.

Vas, P. (1999). *Artificial – Intelligence – Based Electrical Machines and Drives*. Oxford University Press. New York.

Yang, B. S., Han, T. and An, J. L. (2004). Art-Kohonen neural network for fault diagnosis of rotating machinery. *Mechanical System and Signal Processing* **18**, **3**, 645–657.