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A Neural-Network-Based Simulated Model for Controlling Electrical Furnace Using Silicon Carbide Heating Elements

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A R T I C L E I N F O

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A B S T R A C T

It is obvious that Artificial Neural Networks (ANN) is a successful method for system control and simulating nonlinear loads. This paper suggests an ANN model that can simulate the effects of nonlinear Temperature –Resistance characteristic of Silicon Carbide (Sic) load which used as heating elements in the recent electrical furnaces. Moreover, the paper proves that the proposed ANN control model is efficient to aid a conventional control so as keep the power density on the work piece at nearly constant level that is demanded during the heating curing process of the electrical furnace.

Introduction

Electrical Furnaces (EFs) operation depends on the principle of releasing heat energy according to the rule:

$$P=I^2.R \qquad (1)$$

Increasing the current (I), the produced heat energy will increase – keeping resistance (R) constant.

EFs possess many advantages over the –old - combustion furnaces. The temperature uniformity in EF results in greater uniformity of products. Absence of combustion products in EF results in superior quality in many processes. Maintenance costs in EF are lower with shorter production shutdown periods. Greater flexibility of EF permits more efficient use of various operations[1]. The life of superstructure refractory in EF is considerably longer. Heat transfer is fast and controllable in EF[2]. Sic element can be loaded up to 30 w/cm^2 resulting in very high power density in a limited space and fast heating up. Temperature flexibility is of the range (600-1600 ^{0}C) in EF[3] .

Non metallic elements (NMEs) used as heat source in EF are semiconductors doped with a conducting material .The most usual type of NMEs is silicon carbide (Sic) –also called carbonundum- which can be used up to (1600 ^{0}C)[4].

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Heating element (Hot Rod):

Sic- Hot Rod heating elements are manufactured in one piece from high purity Alpha Sic grains sintered at temperatures in excess of (2500 ^{0}C) to form equal diameter recrystallised rods. The maximum recommended element temperature is 1625 ^{0}C[3].

The dimensions of the Hot Rod of Sic that's applied in this paper is shown in **Figure (1).**

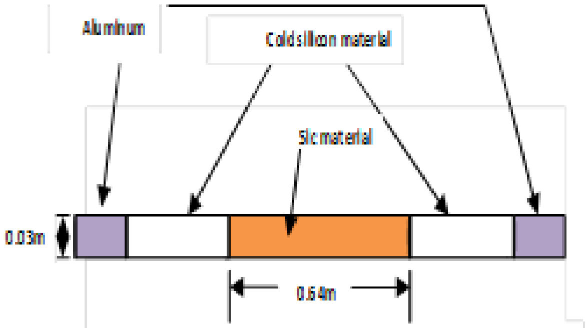

Fig (1) Dimensions of the Hot Rod of Sic

LITERATUR SURVAY:

Nonlinear load modeling has been an important subject for power engineering studies[5]. Different control algorithms (PI, PID, Fuzzy, and Neural controller) have been used for temperature control in furnaces[6]. A literature survey on the recent researches shows a paper of Gary et al (2000) concerning ANN based method of modeling electrical arc furnace load for power engineering study[5]. William E. Staib et al(2007) proposed a Neural Network Electrode Position Optimization[6].

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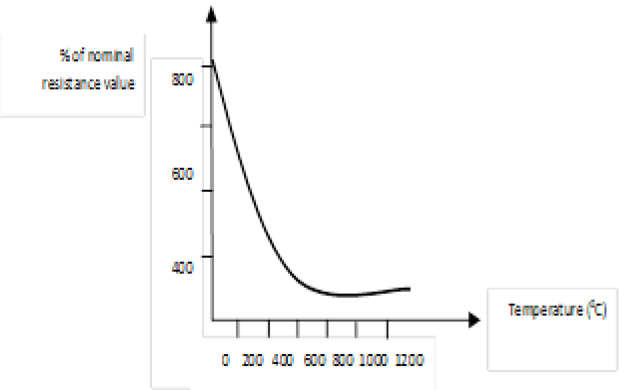
SIC-ELECTRICAL CHARACTERISTICS:

Sic has a much higher resistivity than metallic resistance. Room temperature resistivity is fairly high, and falls with increasing temperature to a minimum value at about (1000 ^{0}C). At element temperatures above (1000 ^{0}C) resistivity increases with rising temperatures. Minute impurities in the material have a disproportionate effect on the resistance value at temperature below (1000 ^{0}C). Resistance measurements taken at room temperature give no indication of the resistance at higher temperatures[3]. **Figure (2)** shows the approximated shape of Sic electrical characteristics. **Table (1)** shows a sample of laboratory data of Sic resistance variation versus applied temperature[3].



Fig(2) :An approximated shape of Sic electrical characteristics

Table (1) A sample of laboratory data of Sic resistance variation versus applied temperature.

No.	Sic element temperature (^{0}C)	% of nominal resistance value
1	0	800
2	200	450
3	400	250
4	600	150
5	800	100
6	1000	100
7	1200	120
8	1400	150
9	1600	175

CALCULATIONS:

Table(1) shows that Sic element reaches its nominal resistance(100%) at about (1000 ^{0}C), and at room ambient temperature (near 0 ^{0}C), nominal resistance is 800%. According to the above data, and by numerical analysis (Least Square Approximation, LSA)[7], Sic temperature- resistance curve can be fitted as in **Figure.(3)**.

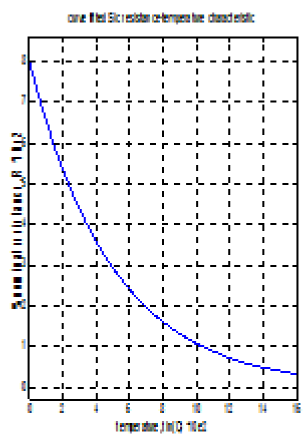


Fig.(3) Curve fitted Sic resistance – temperature characteristics

To design the dimensions of the Sic hot rod - **Figure (1)** - , the following calculations are performed:

$$R = (L/r^2\pi) \times \rho \qquad (2)$$

Where:
(R) is the resistance of the Sic heating element.
(L) is the length of Sic heating element.
(r) is the radius of cross-sectional area of the Sic rode.
(ρ)The resistivity of Sic.
To get R=1 Ohm, we choose: L= 0.64 m, 2r =0.03m.
The resistivity of Sic at 20 ^{0}C =1.1×10^{-3} Ohm.m[8].

EF CONTROL ROBLEM:

Operating-control problems in Sic –based EF happen due to the changes which occur in Sic-element resistance, mainly due to temperature rise. The change in element resistance yields in varying the power supplied to the EF, and this will disturb the uniformity of power density supplied to the piece work (PW) which must stay constant all over the time during the heat curing process.

The two main sources of resistance changes are:

First, the gradual increase in resistance during their life in operation according to the following factors: element type (aging), element specific loading (w/cm^2), operating temperature, process atmosphere, mode of operation, and operating practices[3] .

Second, Sic- temperature characteristics ,**Figure. (2) and Figure.(3)**.

This means that in order to control power supplied to EF, there must be some means for controlling the voltage to the elements. The main way to achieve this is using very expensive transformers with a series of voltage steps and a high voltage power supply. **Figure (4)** shows a control system based on tapped transformer[9].

Recent technology has made it possible to have the same result with Silicon Controlled Rectifier (SCR)[2]. A general Algorithm for the control ideas is shown in **Figure.(5).**

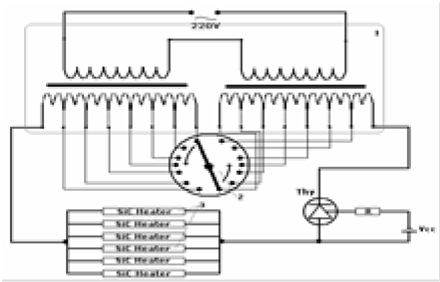


Figure.(4)Power control using transformer

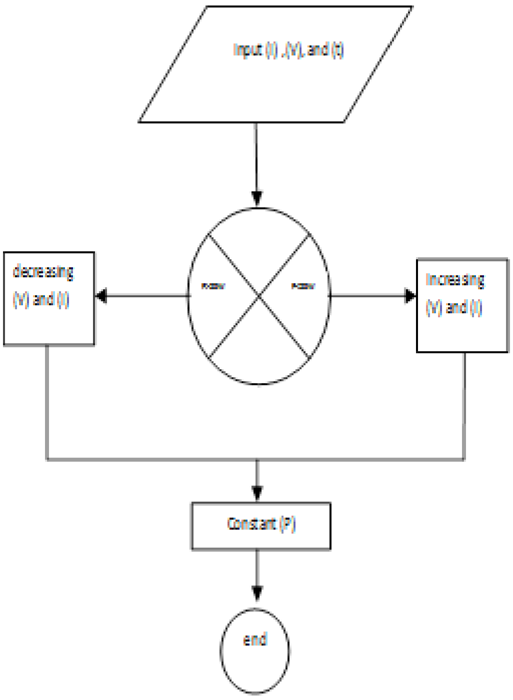


Fig.(7):Proposed control Algorithm

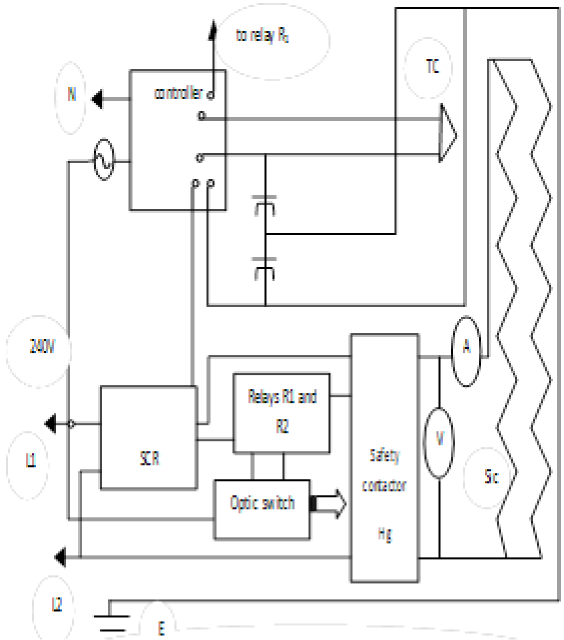
THE CONVENTIONAL (SCR) POWER CONTROL SYSTEM:

Operation Theory:

In **Figure(٦)**, the thermocouple (TC) measure the EF temperature and sends a signal to the temperature controller (T-CONT), which transfers a corresponding signal to SCR. The SCR responds to this signal by proportioning power to Sic elements. It does this by continually varying both the voltage and the current as needed. Should the TC fail, the temperature controller will provide a fail- safe output signal to the SCR. Similarly should there be a power failure, upon restoration of power, a fail-safe output signal is maintained. At high temperature cases, T-CONT actuates an alarm relay (R1), opening the mercury displacement contactor (Hg) and removing power from Sic elements.

At Sic element short- circuit (break down) cases, the current exceeds a pre-set value, and SCR will shut off with an alarm activation. At large load current cases, a current limiting device on SCR will be actuated. At SCR short circuit cases, an alarm relay (R1) will open (Hg) contactor. Optic switch insures cutting the power off during the period of EF gate opening[2].

To keep uniform power density on the WP in the EF, the SCR method depends on proportioning power to Sic via SCR devices by continuously varying (V) and (I). Many disadvantages of SCR control method were recorded, firstly the high possibility of short circuit that may happen in SCR electronic components[2], secondly the errors in measuring devices (Ammeters and voltmeters), thirdly the slow control response as compared with ANN system.



Figure(6)Schematic diagram of SCR EF power control

STEPS OF ANN DESIGN:

The design process of the ANN model goes through the following steps:

1. Preparation of a suitable training data set that represents cases the ANN needs to learn.
2. Selection of a suitable ANN structure for a given application.
3. Training the ANN.
4. Evaluation of the trained ANN using test patterns until its performance is satisfactory.

Sensitivity Importance:

Shahin et al. (2002) proposes a method to test the robustness of the predictive ability of ANN models by carrying out a sensitivity analysis to investigate the response of ANN model outputs to change its inputs. The robustness of the model can be determined by examining how well model predictions are in agreement with the known underlying physical processes of the problem in hand over a range of inputs[9].

ANN Training Procedure :

The general strategy adopted for finding the optimal network architecture and internal parameters that control the training process is as follows:

A number of trials are carried out using the default parameters of the software used with one hidden layer and (1, 2, 3, 4, 5, 6, and 7) hidden layer nodes[11].

The network that performs best with respect to the testing set is retrained with different combinations of momentum terms, learning rates and transfer functions in an attempt to improve model performance.

The model that has the optimum momentum term, learning rate and transfer function is retrained by a number of times with different initial weights until no further improvement occurs. **Figure.(٧)** shows that the network with (2) hidden layer nodes has the lowest prediction error for testing set .

The effect of the momentum term and the learning rate on model performance are shown graphically in **Figure.(٨)**and **Figure.(٩).** It can be seen that the performance of the ANN model is sensitive to momentum terms.

The optimum values for momentum term and learning rate used are (0.95 and 0.99) respectively .The hyperbolic tangent (tanh) transfer function is used for the hidden layer and the sigmoid transfer function is used for the output layer.

The Designed ANN Architecture :

The designed ANN architecture is shown in **Figure(١٠).** The ANN was trained to match the target (P). **Figure (1١)** shows the predicted and the actual values of (P). **Table (٢)** shows weights and threshold levels for the ANN model that's considered as an optimal final model. **Figure. (1٢)** shows a comparison of the relative importance of the three inputs applied to the ANN. It is clear that the most important factor in keeping (P) constant is the current. This result agrees with the rule ($P=I^2.R$).

THE PROPOSED ANN-AIDED CONTROL MODEL:

An approximated experimental data concerned a hot rod of Sic that belongs to an EF was estimated[3]. The readings of the temperature degree (t), the resistance of the Sic Element (R), the input current (I), and the total power supplied to the WP (P) were induced from that available data.

The three input vectors (t, R and I), were supplied to a well designed ANN of figure.(10), with the vector (P) as the output vector.

A study was made to choose the best number of hidden layer nodes, momentum terms, and learning rate.

Sigeru Omato et al introduce a parallel Neuro-Control Architecture as shown in Figure.(13) where a PID controller is used as the conventional controller[12], we develop a similar Scheme to control our EF, Figure.(14) illustrates the main parts of this scheme where the voltage, current and temperature signals are converted to digital by (A/D) converter unit. The output signal (r) is fed to both conventional (SCR) and the well trained ANN units. Output signal of the conventional unit (r1) is compared with the reference signal (r0), (K is a suitable constant); if it is suitable then (r1) is implemented to the V-I Correction unit, else, a control- signal (e) is fed to excite the ANN unit. In this case ANN (r2) control- signal will replace (r1) signal to correct input (V) and (I). This procedure will insure the demanded constant power (P) supplied to the (WP).

RESULTS AND CONCLUSIONS:

1: The elementary experimental recordings of heat temperature, Sic resistance, input voltage and current are estimated. The (t) and (R) readings are manipulated by LSA numerical analysis, and an approximated function of (R) vs. (t) is constructed and plotted.

2: This data is implemented in the design and the training of ANN that aides the work of the conventional SCR control system so as to maintain constant power supplied on to the WP.

3. This research put the first step to represent the nonlinear Sic resistance in the power analysis study of the electrical power systems.

4: The paper proves that the major disadvantage of high nonlinearity of (R vs. t) characteristics concerning Sic heating element can be overcome by the aid of well designed ANN unit, especially when it is essential to raise the temperature of the WP to very high levels like that accomplished in EF using Sic heating elements.

5: Further work will include finding the transfer function which can be used to represent the EF in the total mathematical model of the power system.

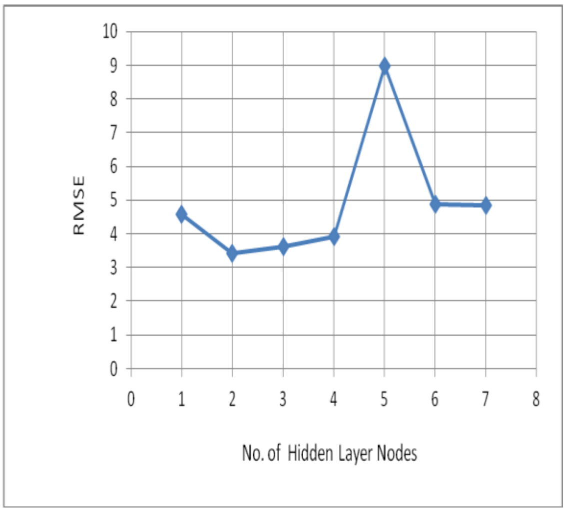


Figure.(7): Performance of the ANN model with different hidden layer nodes

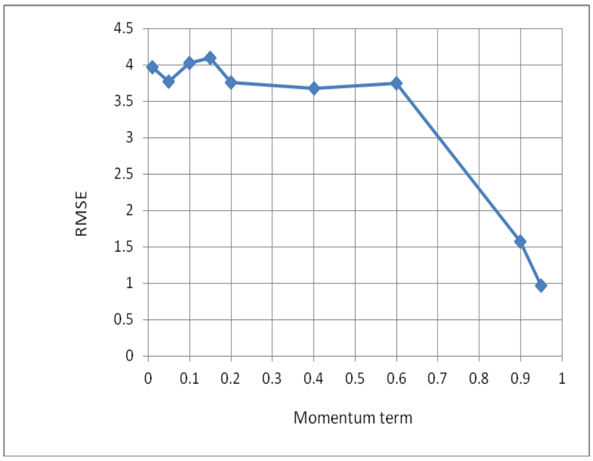


Figure.(8):Effect of various momentum terms on ANN performance (Hidden nodes = 2 and Learning rate = 0.2)

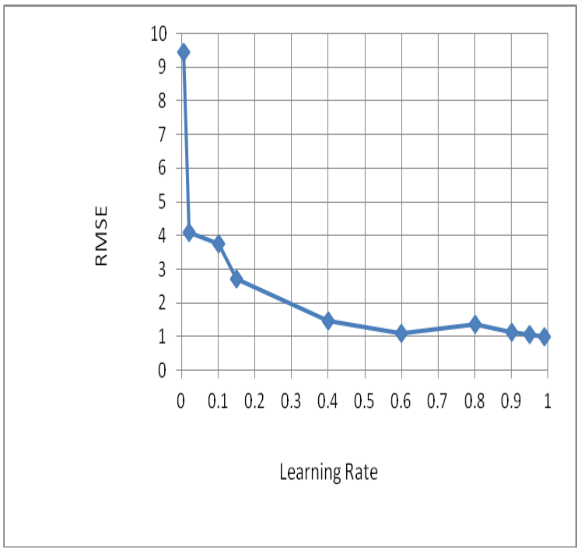


Figure.(9):Effect of various learning rates on ANN performance (Hidden nodes = 2 and Momentum term = 0.8)

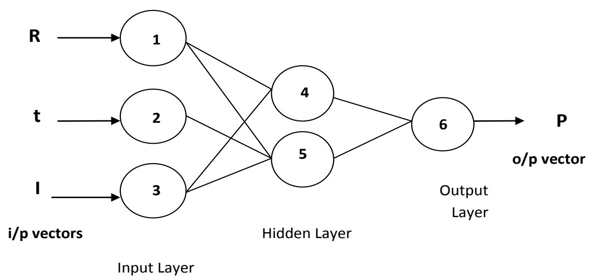


Figure.(10) the designed ANN architecture

Table (2): Weights and threshold levels for the ANN optimal model

Hidden layer nodes	w_{ji} :weight from node (i) in the input layer to node (j) in the hidden layer			Hidden layer threshold θ_j
	i=1	i=2	i=3	
j=4	0.960183	-0.24757	-0.5659	0.167422
j=5	0.154485	-0.38535	-0.53522	0.125589
Output layer nodes	**W_{jk} :weight from node (j) in the hidden layer to node (k) in the output layer**			**Output layer threshold θ_k**
	i=4	i=5	-	
k=6	1.637335	0.452991		0.343036

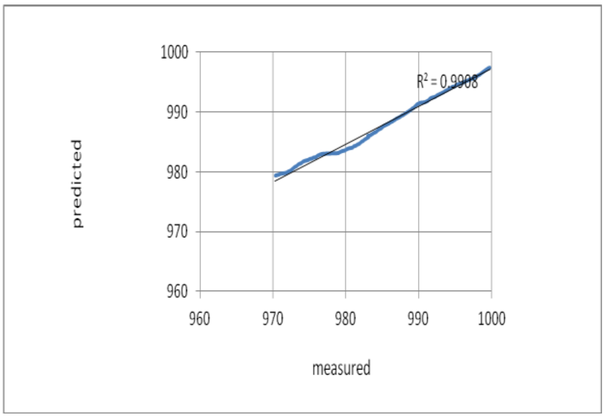


Figure.(11) The predicted and the actual curves of (P).

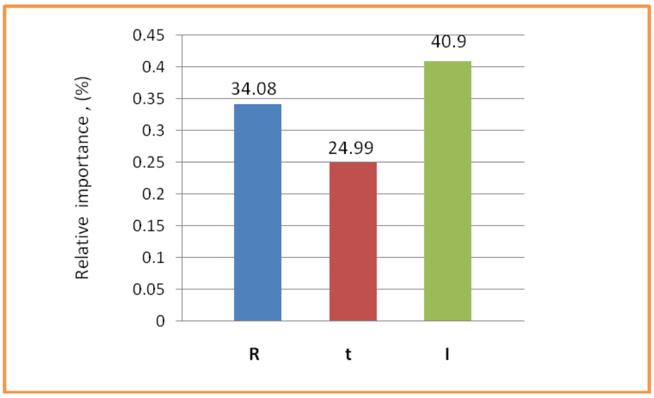


Figure.(12)Relative importance of the input variables for ANN model

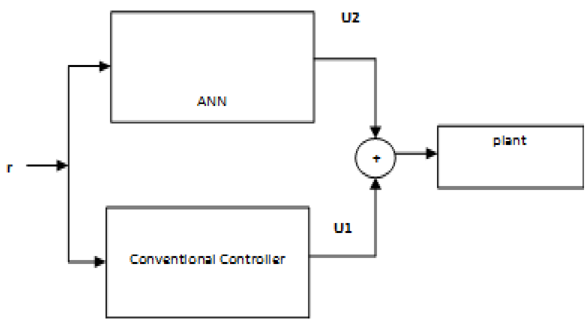


Figure (13) parallel neuo-control schem

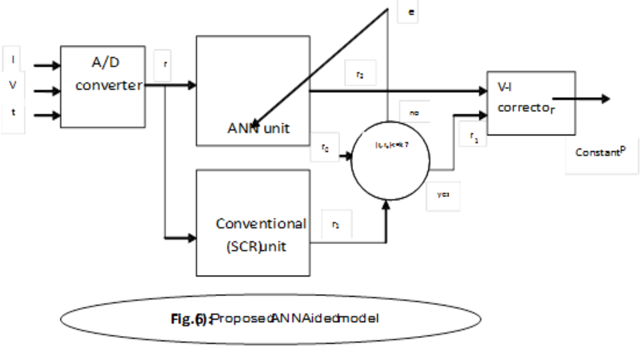


Figure (14) Proposed ANN Aided Model

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SYMBOLS:

quantity	description	unit
I	the electrical current	Amper
L	length	Meter
P	Electrical power	Wat
r	radius	Meter
R	Resistance	Ohm
t	temperature	0C
W_{ij}	weight from node i in the input layer to node j in the hidden layer	non
Θ_{jk}	Hidden and output layer threshold	non
RMSE	Root of Mean Squares Error	Watt
R^2	Coefficient of determination	non

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تصميم دائرة شبكات عصبية اصطناعية كنموذج محاكاة لعملية السيطرة على فرن كهربائي يستعمل كاربايد السليكون

سهيل محمد علي

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الخلاصة:

من الواضح أن الشبكات العصبية الاصطناعية تعد طريقة ناجحة في الاستعمال في منظومات السيطرة ولمحاكاة الأحمال غير الخطية. تقترح هذه الدراسة نموذج شبكة عصبية اصطناعية تستطيع محاكاة تأثيرات الخصائص غير الخطية للعلاقة بين درجة الحرارة والمقاومة لمادة (كاربايد السليكون) المستعملة كعنصر تسخين في الأفران الكهربائية الحديثة. إضافة إلى هذا، فإن البحث برهن أن نموذج السيطرة المقترح هو كفء في المساعدة للمحافظة على ثبوتية كثافة القدرة المستعملة للتسخين والمسلطة على قطعة الشغل داخل الفرن؛ وهو الأمر الضروري في أحيان كثيرة أثناء عمليات المعالجة الحرارية في الفرن الكهربائي.