Optimization Corrosion Protection Parameters of Steel Pipeline by Using Taguchi Experimental Design

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Abstract
Cathodic Protection System (CPS) is used to reduce corrosion by minimizing the difference in potential between anode and cathode. Two types of Cathodic protection systems are usually applied: The galvanic protection systems use the sacrificial anodes, the other system is impressed current (that used in this paper), and this can be achieved by applying a current to the structure to be protected from electrical source. The main objective of this work is to determine experiments designed according to Taguchi method and Analysis the results by MINITAB program. Experiments have been conducted by using L9 orthogonal array with three parameters (concentrations of NaCl solution, Temperate and Speed of Solution) at three levels (low, medium and high). The result of research based on the signal to noise ratio (S/N) depending on the condition smaller is better approach. The results of this paper show that the significant factor is NaCl wt% and the optimum combination of parameters which were reducing the corrosion are temperature (35 °C), the speed of solution (15 r.p.m) and the NaCl concentration (20 %wt).

Key-words: Cathodic Protection, Impressed Current, Taguchi Method, MINITAB Program.

أمثلية عوامل الحماية من التآكل للأنابيب الفولاذية باستخدام التصميم التجريبي لتاكوشي

الخلاصة
يستخدم نظام الحماية الكاثودية لتقليل التآكل بواسطة تخفيض الاختلاف في الجهد بين الانود والكاثود. وعادتاً يتم تطبيق نوعين من انظمة الحماية الكاثودية وهما: نظام الحماية الكلفاني وفية يتم استخدام اقطاب مضحية والنظام الاخر هو التيار المسلط (والذي تم استخدامه بهذا البحث)وهذا يمكن ان يتم بواسطة تسليط تيار على التركيب المراد حمايته من مصادر للتيار الكهربائي. يهدف البحث لتصميم التجارب بالاعتماد على طريقة تاكوجي ويتم تحديد الامثلية اعتماداً على برنامج (MINITAB program).في التجارب العملية تم استخدام مصفوفه رياضية L9 والتي تكون بثلاث عوامل اساسية (نسبة NaCl ودرجة الحرارة وسرعة حركة المحلول) وهذا يتم عند ثلاث مستويات (منخفض ومتوسط وعالي). نتائج البحث اعتمدت على نسبة الاشارة الى الضجيج (S/N) اعتماداً على الحالة الاصغر هي الافضل. تبين نتائج البحث ان العامل الاكثر تأثيراً في التأكل هو نسبة

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NaCl والظروف الامثل لتقليل التأكل هي عند درجة حرارة (35 °C) وسرعة المحلول (15 r.p.m) ونسبة NaCl (20 %wt).

الكلمات المرشدة: حماية كاثودية، طريقة تاكوشي، التيار المؤثر، برنامج MINITAB

INTRODUCTION

Cathodic protection (CP) design of 'conventional' steel structures in soil or water is a well-established discipline which involves an estimate of the size and geometry of the structure to be protected, current requirement calculations and a design of the most suitable type and size of ground bed. [1].

The amount of corrosion is dependent on the metal being used as an anode and is directly proportional to the amount of current supplied. Another factor is the anode efficiency, which accounts for the anode's self-corrosion rate and the corrosion rate for the amount of cathodic protection current. The effects of corrosion often require costly repairs and continued maintenance during a structure's life [2]. Formation water as formation water medium contains dissolved salt with varied salinity [3,4]. Increasing NaCl concentration in the solution also increase the conductivity of the solution. However, this condition will affect the solubility of dissolved gases, which act as reducing agent in the kinetics of corrosion processes which will affect the steel corrosion rate on its environment [5].

There is more than one factor (parameter) affects any manufacturing process or protection process in general. In protection operation, there are many factors taken into consideration during the experimental test [6]. The purpose of this paper is to discuss the various factors which the designer should consider and give some pointers to provide a satisfactory CP design [1]. In addition to this, if each factor has more than one level, the result will be a plenty of experiments. In case of increasing of the levels or the factors, the number of experiments will certainly increase too. Therefore, the need to reduce these experiments is so necessary. A statistical experimental design method named "Taguchi method" is the method that is presented for this purpose [6,7]. The Taguchi methods that were developed as an aid of quality assurance in Japanese industries are among the most powerful approaches to understand the process and optimize its performance. Taguchi described his methods as quality engineering. This assists the industrial engineers to prove near optimal quality characteristic or (response) for a specific objective within determining the best combination of parameters. This can be achieved only by making the process insensitive to various sources of noise and the method is called robust parameter design [7,8]. The aim of this work is determining the optimal state of steel pipeline under corrosion protection by using Taguchi experimental design at different parameters.

Experimental works

Materials

High strength steel pipeline was used in this study and analyzed by the Specialized Institution of Engineering Industries-Baghdad. Their chemical compositions are shown in Table (1).

Table (1). Chemical compositions of the steels used in the tests (wt. %)

Components	C	Si	Mn	Cr	Mo	S	Ni	P	Fe
Steel pipeline	0.14	0.12	0.45	0.017	0.011	0.0	--	0.01	Balanc

Surface preparation

Surface preparation is the most important step in the application of any Electrochemical Testing, in this work, the specimens cut from the oil steel pipeline, the cutting achieved by cutting machine; it's taken from the Iraqi Oil Pipelines Company/ Ministry of Oil. Where the specimens prepared for Electrochemical Testing by Grinding process with dimensions of the specimen were (1.5cm length and 1.5cm width), was carried out by using disk rotary instrument with different grades of emery papers (SiC) in sequence of (220, 320, 500, 800 and 1000) grit to get facing free surface.

The specimens were washed with water and alcohol and dried in the air, polished process was carried out by using special polishing cloth and alumina (Al_2O_3) solution of grain size of (0.3μm).

Electrochemical testing

An electrochemical corrosion test was carried out by the potentio-dynamic anodic polarization using Potentiostat Galvanostat instrument according to the ASTM Standard G-5 [9]. All of the electrochemical corrosion tests were performed using three-electrode electrochemical probes with electrodes made of the same material and surface area. The Corrosion Rate C.R, was calculated using the following formula:

$$C.R\,(mpy) = 0.13 * I_{corr} * e/\rho \quad (1)$$

Where:

mpy: mils penetration per year, 1 mils= 10^{-3} inch

I_{corr}:corrosion current intensity (A/cm^2).

ρ: matail intensity (gm/cm^3).

e: atomic weight.

Distilled water was used to prepare sodium chloride solution, the NaCl solution was taken according to the Iraqi soil, which was equivalent with NaCl solution, and connected with Potentiostat device (Wenking LT87-Germany) as shown in Figure (1).

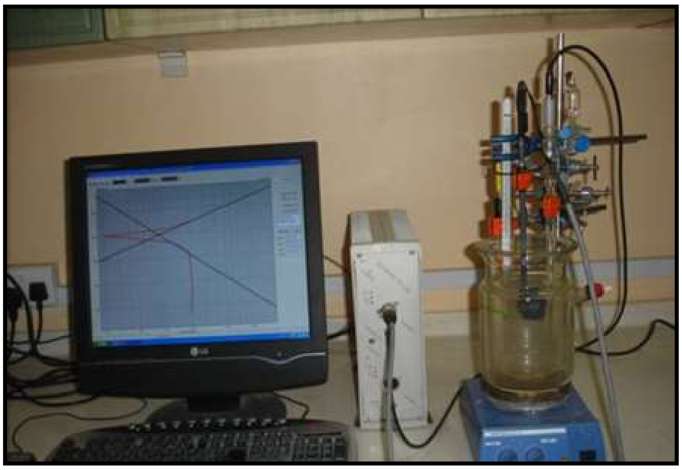

Figure (1).Potentiostat (Wenking LT87-Germany)

Taguchi method

Taguchi method has been used in the current study to optimize the setting of the parameters that usually affect corrosion protection operation that analysis by (MINITAB program) [7]. The optimization based on Taguchi approach can economically satisfy the needs of problem solving and product /process design optimization projects in the manufacturing industry. By studying and applying this technique; engineers, scientist, and researchers can significantly reduce the time required for experimental investigations and provide near optimal equality characteristic for a specific objective [10,11]. The experiments were conducted under Taguchi experimental design method with the aim to determine and optimize parameters that may have influenced on corrosion protection. The method used a design of orthogonal arrays that allowed minimizing the number of experiments while keeping a good accuracy in the results and interpretation, a model of 3 parameters with 3 levels (9 orthogonal arrays) each was considered, as shown in Table (2).

Table (2). Control Factors

Levels of experimental factors	Experimental factor		
	NaCl ratio wt%	Temperature of Solution C°	Solution Speed r.p.m
1	15	300	5
2	20	35	10
3	35	45	15

The L9 orthogonal array with three columns and nine rows was an appropriate selection in this study. The factors and levels for surface roughness are arranged as shown in Table (3) such that each row of this table represents an experiment with different combination of factors and their levels. According to L9 array, nine specimens were prepared to be machined and measured.

Table (3). The Taguchi L9 orthogonal array

Experiment Number	Corrosion parameter parameters level		
	A	B	C
	NaCl ratio wt%	Temperature of Solution °C	Solution Speed r.p.m
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The variable parameters were: i) parameter 1 is the NaCl concentration in solution; ii) parameter 2 is the Temperature of the solution; iii) parameter 3 is the Speed the solution. The values of each parameter at each level have been summarized in Table (4).

Table (4). Orthogonal Array L9 of Taguchi Method with variable parameters.

Experiment No.	NaCl wt%	Temperate ° C	Soultion Speed r.p.m
1	15	30	5
2	15	35	10
3	15	40	15
4	20	30	10
5	20	35	15
6	20	40	5
7	35	30	15
8	35	35	5
9	35	40	10

The response variables chosen for the present investigation are Corrosion current density. The lower-the better quality characteristic has been used for calculating the signal to noise (S/N) ratio for these responses, see Eq. 2.[11,12]

$$S/N = -10 \log 1/n (\sum_{i=1} y^2) \quad (2)$$

Where:
Y: is observed response value at each trail
N: is the number of observations in each trial

Results and discussion

Using Minitab software ANOVA for S/N can be computed for all factors, Minitab software used to analysis the results. The conditions combination for the three corrosion parameters: NaCl concentration, Temperature of the solution, and Speed the solution as shown in Table (2) according to their places in the orthogonal array L9 shown in Table (3). These conditions are considered as input (inner array). The Corrosion current density (Icorr) was calculated as an average for three different measurements for each experiment. Because the Signal-to-Noise ratio (S/N) should be as small as possible, the quality characteristic “smaller is better” was used. S/N values were calculated from eq. (2), and the results have been arranged in the last column of array.

S/N ratio represents the output (outer array) in that array. Depending on n factor, the total number of values obtained is (n * experiment no. = 3 * 9 = 27 values) [7,13]. The results were analyzed by using main effects for Signal-to-Noise ratio (S/N), and ANOVA analyses. Then, a confirmation test was carried out to compare the experimental results with the estimated results. Depending on the results in Table (5) can be determined the S/N ratio by using Eq. (2).

Table (5). The Results Corrosion Rate Depending L9 of Taguchi Method

Experiment No.	Corrosion potential E_{corr} /mv	Corrosion current density IcorrμA/cm2	Corrosion rate (mpy)
1	-536.0	3.91	0.839
2	-534.5	6.15	1.319
3	-537.0	7.73	1.658
4	-433.9	3.93	0.843
5	-413.3	3.45	0.740
6	-497.3	13.18	2.827
7	-497.2	7.62	1.634
8	-528.5	11.4	2.445
9	-503.1	10.02	2.149

The S/N ratio for the smaller has better quality characteristic used in this study and is calculated by equation (2): The results as shown in table (6).

Table (6). S/N ratio for experimental trials

Experiment No.	S/N Ratio
1	-11.8435
2	-15.7775
3	-17.7636
4	-11.8879
5	-10.7564
6	-22.3983
7	-17.6391
8	-21.1381
9	-20.0174

After the S/N is obtained the average performance of each factor is calculated at each level and table (7) shows the result of that. Plot the average S/N value of each factor is shown in Figure (2).

Table (7). The S/N Ratio Average Values (Raw Data: Ci)

Process parameter Designation	Average values of S/N table for factors			Delta	Rank
	L1	L2	L3		
A	-15.13	-15.01	-19.60	4.58	2
B	-13.79	-15.89	-20.06	6.27	1
C	-18.46	-15.89	-15.39	3.07	3

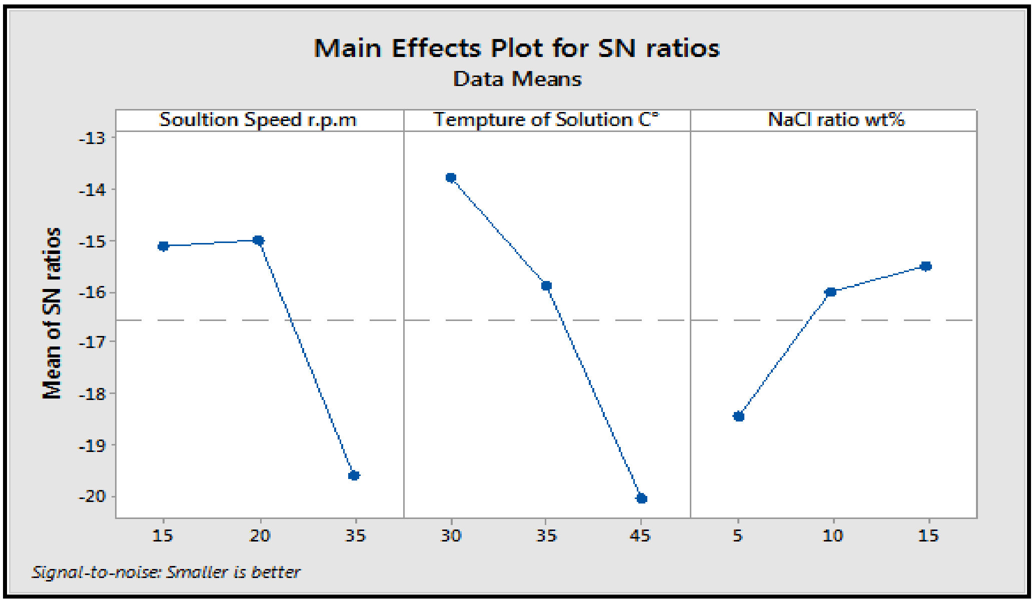

Figure (2). Main Effect Plot for S/N Ratio

Table (8) shows the ANOVA of S/N for all factors, depending on the information of the ANOVA table the percentage contributions of the factors can be computed. Compute the percentage contributions for factors to explain the significance of factor affected in S/N. Figure (2) shows the percentage contribution of the factors.

Table (8). ANOVA for S/N Ratio

Source	DOF	Adj SS	Adj MS	F-Value	P-Value	Contribution %
NaCl ratio wt%	2	41.01	20.503	1.39	0.419	27.7132
Temp. of Solution C°	2	61.10	30.551	2.07	0.326	41.2894
Soultion Speed r.p.m	2	16.29	8.144	0.55	0.645	11.0082
Error	2	29.58	14.79	-	-	19.9892
Total	8	147.98	-	-	-	100 %

Where:
mean squares = sum of squares / DOF.
F- ratio = mean squares of factor / mean squares for error.
P% = sum of squares of factor /total sum of squares.
By depending on the information in Table (8) and Figure (2), Temperature of Solution can be obtained that is the most significant factor that affects the S/N ratio followed by A (Current) and t (Time), and the optimal levels for the factors are:
1- The temperature at first level.
2- The Solution Speed at second level.
3- The NaCl concentration at third level.

Conclusions

This paper discussed an application of the Taguchi method for optimizing the corrosion protection parameters of steel pipeline. Some conclusions can be summarized depending on the experimental results as the following :

1. The Taguchi method provides a systematic and efficient methodology for the design and optimization of corrosion protection parameters with far less effort than would be required for most optimization techniques.
2. The optimal levels by applying Taguchi method in corrosion protection to increase the resistance of corrosion are: The temperature is (35 °C) the speed of solution (15 r.p.m) and the NaCl concentration (20 %wt).

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