Use of Experimental Box-Behnken Design for the Estimation of Interactions Between Harmonic Currents Produced by Single Phase Loads

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Abstract

In this paper, it is aimed to deal with the interactions of harmonic currents produced by different single phase loads. For this purpose, compact fluorescent lamps, incandescent lamps, and electric heaters were chosen as single phase loads. The study was performed by adopting a full range of response surface methodology using Box–Behnken experimental design to express the net harmonic current (3rd and 5th) as an empirical model. The model provided an excellent explanation of the relationship among the number of loads and the net harmonic currents. Contour graphs of some of the harmonic currents was plotted to show the interactions clearly and to discuss the results of model in the graphic detail. The results of experiments showed that the harmonic interaction between the loads can be defined as a regression model which is statistically significant.

Keywords: Box-Behnken Design, Harmonic Currents, Harmonic Distortion, Single Phase Loads

I. INTRODUCTION

In recent years, the increase in the number of non-linear loads (NL) connected to the distribution systems has resulted more serious harmonic pollution which obligate researchers to analyze the harmonics in more detailed. Although, lots of studies related with harmonic current take place in literature, it is obvious that lots of new researches on this subject have to be performed because of the comprehensive nature of the topic and also inserted new harmonic sources to the distribution system.

Most certainly, TV sets, fluorescent lamps, most office appliances (printers, computers, etc.), transformers, rotating machines, and arc furnaces find acceptance as harmonic sources [1, 2]. These harmonic sources may cause in the following: (i) overheating or derating of transformer, (ii) overheating of wiring, (iii) damaging of capacitor banks, (iv) resonance, (v) malfunction of electronic equipment, (vi) communication interference, (vii) distorted supply voltage [3-5]. These drawbacks mentioned above make the researches about the harmonics more important.

Most of studies in the literature state that harmonic currents produced by NL vary randomly since their operating modes are changing. In one of them, it was expressed that the vectorial sum of the net harmonic current produced by six different desktop computers is less than that of the magnitude [6]. Therefore, studies related with harmonic phenomena should be carried out by taking into consideration the importance of the probability characteristic of harmonics. For example, ac/dc static power converters were investigated by some authors with the aid of probability. The probability density functions (PDF) of magnitude of vectorial sum of harmonic currents produced by converters was presented and the sum of harmonic currents related with 3, 5, and 10 converters was compared with the results of Monte Carlo simulation [1].

The widespread use of computers, televisions, and light dimmers is also one of the causes of harmonic distortions. Therefore, the magnitudes and phase angles of the net harmonic currents due to television and light dimmer were investigated [7]. Time-varying characteristics of harmonic spectrum of desk top PC and printers illustrated experimentally [8], and time-domain models of single-phase NL like PC, fluorescent lamp, and UPS (uninterruptible power supply) were presented [9]. In addition, the harmonic effects of photocopier and cell phone battery charger were investigated and harmonic currents versus power demand regression curves were plotted and discussed [10].

In this paper, we peoposed an approach to illustrate the interaction of harmonic currents caused by three different single phase loads such as incandescent lamp, electric heater, and compact fluorescent lamp by the aid of Box-Behnken experimental design. The responsibility of the each load to the net harmonic currents has been defined as an empirical model and the results have been discussed statistically.

II. Description of the Measurement Campaign

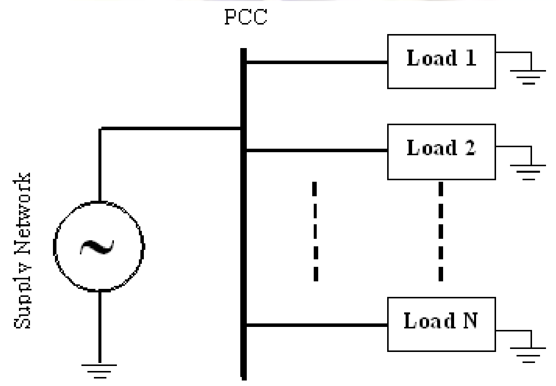
Equipment

In the context of the experiments, incandescent lamps, electric heaters, and compact fluorescent lamps were chosen as single phase loads which find widespread usage in low-voltage distribution systems. Their electrical properties are given in Table 1 and experimental setup illustration is shown in Figure 1.

Table 1. The properties of single phase loads used in experiments

	Incandescent Lamp	Electric Heater	Compact Fluorescent Lamp
Nominal power, W	40	530	20
Frequency, Hz	50/60	50/60	50/60
Voltage, V	220-230	220-230	220-240

Figure 1. The experimental setup illustration



Harmonic currents' magnitudes were measured by Power Quality Analyzer (Fluke 43B) according to the experimental design [11]. The time-varying nature of harmonics was taken into consideration to get more significant results. For this purpose, 30 measurements in 5 minutes were performed for each experiment and the average values were examined to use into the experimental design. The factors affecting the resultant harmonic current such as the load supplying impedance, the magnitude of individual loads, and the applied voltage were not taken into consideration in the context of this experimental design. Because the aim of this study is just to clarfy the affects of the number of connected load and interactions of them.

Experimental design

The experiments were performed according to the Box-Behnken design which is a kind of response surface methodology. It is well known that response surface methodology, or RSM, is a collection of mathematical and statistical techniques useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [12-15]. It is an empirical modelization technique devoted to the evaluation of the relationship of a set of controlled experimental factors and observed results [16].

To analyze a process mutually with a response, Y which depends on the input factors X_1, X_2, …, X_n, the correlation between the response and the input process parameters are described as

$$Y = f(X_1, X_2, \ldots, X_n) + \varepsilon \qquad (1)$$

where f is the real response function its format being unknown, and ε is the residual error which describes the differentiation that can be incorporated by the function f. Because the correlation between the response and the input variables can be described as a surface of the X_1, X_2, …, X_n coordinates in the graphical sense, so the investigation of these relationships is named as the response surface study [12, 17].

Some three-level designs which have been proposed by Box and Behnken are formed by combining 2^k factorials with incomplete block designs. Box-Behnken design does not contain any points at the vertices of the cubic region created by the upper and lower limits for each variable; which means the reduced number of required runs. This could be advantageous when the points on the corners of the cube represent factor-level combinations that are prohibitively expensive or impossible to test because of physical process constraints [12, 18]. Although, the Box-Behnken design has been used for design of experiments in various industrial applications [16, 17, 19-22], it can be told that it will find usage in the design of experiment related with determination of harmonic currents produced by the different single phase loads by the aid of this study.

The variables like the number of heater, compact fluorescent lamp, and incandescent lamp were chosen as the critical variables and designated as X_1, X_2 and X_3 respectively. The low, middle, and high levels of each variable were designated as -1, 0, and +1 respectively, and given in Table 2. The actual design of experiments is given in Table 3.

Table 2. The levels of variables chosen for the trials

Level of variable	Number of variables		
	Heater, X_1	Compact Fluorescent Lamp, X_2	Incandescent Lamp, X_3
-1	0	0	0
0	1	1	1
+1	2	2	2

Table 3. The Box-Behnken design for the three independent variables

Trial No.	Level of variables		
	Heater	Compact Fluorescent Lamp	Incandescent Lamp
1	1	0	1
2	0	-1	-1
3	0	-1	1
4	1	0	-1
5	1	-1	0
6	-1	0	-1
7	-1	0	1
8	1	1	0
9	0	0	0
10	0	0	0
11	0	1	-1
12	0	1	1
13	-1	-1	0
14	-1	1	0
15	0	0	0

In a system involving three significant independent variables (X_1, X_2 and X_3) the mathematical relationship of the response on these variables can be approximated by the second order polynomial equation:

$$Y = \beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_{12}X_1X_2+\beta_{13}X_1X_3+\beta_{23}X_2X_3+\beta_{11}X_1^2+\beta_{22}X_2^2+\beta_{33}X_3^2 \qquad (2)$$

Where, Y is the dependent variable (3rd (I_3) and 5th (I_5) harmonic current); X_1, X_2 and X_3 are the levels of independent variables (number of heater, compact fluorescent lamp, and incandescent lamp respectively); β_0 is the regression coefficient at the center point; β_1, β_2 and β_3 are linear coefficients; β_{12}, β_{13} and β_{23} are quadratic coefficients. The quality of the fit of the polynomial model equation was expressed by the coefficient of determination, R^2. The reason is why 3rd and 5th harmonic currents are chosen as dependent variable is being the highest harmonic currents produced by the single phase loads. For the evaluation of results, a statistical program was used.

III. Results and Discussion

By applying regression analysis methods, the predicted response for 3rd and 5th harmonic currents (I_3 and I_5) have been obtained and given as

$$I_3=0.01611+0.01011\times A+0.02883\times B-0.02061\times C-0.034402\times A\times B+0.00155\times A\times C-0.003775\times B\times C+0.02072\times A^2+0.013845\times B^2+0.012147\times C^2 \qquad (3)$$

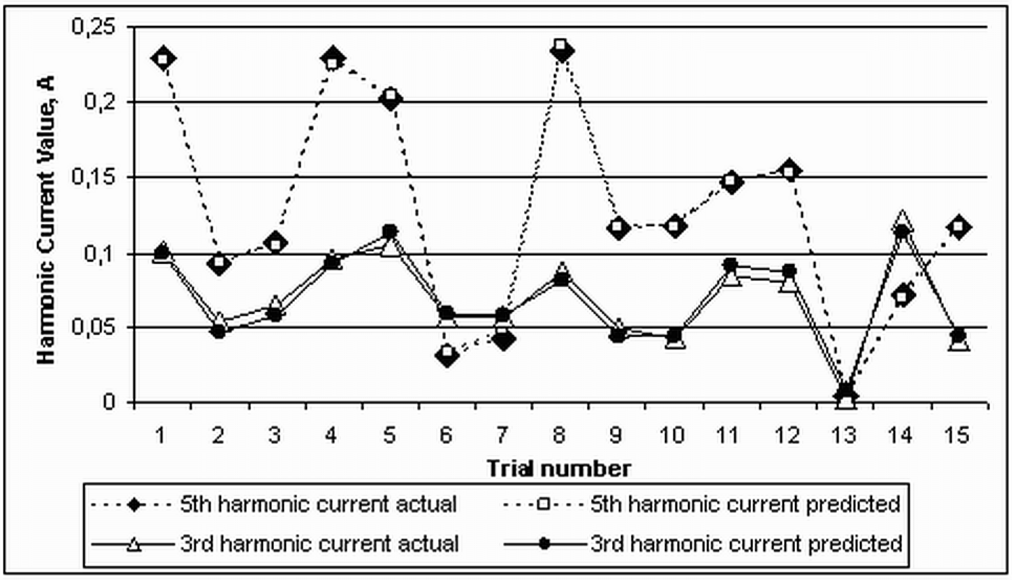
$$I_5=-0.000656+0.084519\times A+0.032906\times B-0.004490\times C-0.008628\times A\times B-0.002900\times A\times C-0.001275\times B\times C+0.009799\times A^2+0.001224\times B^2+0.006501\times C^2 \qquad (4)$$

Where I_3 and I_5 are the predicted response for 3rd and 5th harmonic currents and A, B and C are the coded values of the test variables, the number of heater, compact fluorescent lamp, and incandescent lamp respectively. The actual and predicted values are shown in Table 4 and illustrated in Figure 2.

Table 4. Experimental and theoretical predicted values for 3rd and 5th harmonic currents

Trial No.	3rd harmonic current, I_3 (A)		5th harmonic current, I_5 (A)	
	Actual Value	Predicted Value	Actual Value	Predicted Value
1	0.10100	0.09911	0.22900	0.22733
2	0.05400	0.04695	0.09190	0.09366
3	0.06440	0.05742	0.10600	0.10489
4	0.09490	0.09309	0.22900	0.22445
5	0.10500	0.11386	0.20100	0.20379
6	0.05690	0.05879	0.03180	0.03347
7	0.05680	0.05861	0.04340	0.04795
8	0.08690	0.08174	0.23400	0.23744
9	0.04980	0.04453	0.11600	0.11700
10	0.04280	0.04453	0.11800	0.11700
11	0.08420	0.09118	0.14600	0.14711
12	0.07950	0.08655	0.15500	0.15324
13	0.00249	0.00766	0.00479	0.00136
14	0.12200	0.11314	0.07230	0.06951
15	0.04100	0.04453	0.11700	0.11700

Figure 2. The actual and predicted 3rd and 5th harmonic currents



The analysis of variance (ANOVA) for response surface quadratic model is summarized in Table 5 for both of the 3rd and 5th harmonic currents. It also consists of *F*-test results which define the statistical significance of Eqs. (3) and (4). When the *P*-values of regression models are taken into consideration, it can be told that the models of 3rd and 5th harmonic current, which have less than 0.05 P-value, are statistically significant at the 95% confidence level. The closer the values of R to 1, better the correlation between the experimental and predicted values. Here, the values of R^2 (0.9650 and 0.9990) for both of the 3rd and 5th harmonic currents indicate good relation between the experimental and predicted values of the response. Meanwhile, achieving nearly same actual and predicted values as a result of experimental design confirm the usability of the empirical model for this study (Table 4 and Figure 2). The lack-of-fit measures the failure of the model to represent data in the experimental domain at points which are not included in the regression. The non-significant value of lack of fit (>0.05) revealed that the quadratic model is statistically significant for the 3rd harmonic current.

Table 5. ANOVA test results for the regression of 3rd and 5th harmonic currents

	Source	df	Sum of squares	Mean squares	*F*-value	Frequency (P)
3rd Harmonic Current $R^2 = 96.5\%$, Adj. $R^2 = 90.2\%$	Regression	9	0.012798	0.001422	15.32	0.004
	Linear	3	0.005505	0.000318	3.42	0.109
	Square	3	0.002492	0.000831	8.95	0.019
	Interaction	3	0.004801	0.001600	17.24	0.005
	Residual	5	0.000464	0.000093		
	Lack of fit	3	0.000421	0.000140	6.49	0.136
	Pure error	2	0.000043	0.000022		
5th Harmonic Current $R^2 = 99.9\%$, Adj. $R^2 = 99.6\%$	Regression	9	0.074729	0.008303	428.85	0.000
	Linear	3	0.073914	0.001565	80.84	0.000
	Square	3	0.000477	0.000159	8.22	0.022
	Interaction	3	0.000338	0.000113	5.82	0.044
	Residual	5	0.000097	0.000019		
	Lack of fit	3	0.000095	0.000032	31.60	0.031
	Pure error	2	0.000002	0.000001		

The coefficients at the Eqs. (3) and (4) indicate the responsibility of each independent variable (number of heater, compact fluorescent lamp, and incandescent lamp) and also interactions of them. For example, higher coefficient value of B (+0.02883) than A (+0.01011) in Eq. (3) means that the effect of compact fluorescent lamp on to the 3rd harmonic current is higher than that of the electric heater, although the nominal power of electric heater is highest. Meanwhile, the interaction of the electric heater and the compact fluorescent lamp ($A \times B$), with -0.034402 coefficient value, has a reducing effect. On the other hand, the highest coeffecient value (+0.084519) among the variables belongs to A in Eq. (4). This means that the biggest effect on to the 5th harmonic current caused by the electric heater. Compact fluorescent lamp seems as the second important variable in terms of 5th harmonic current. Although compact fluorescent lamp cause increase in the 5th harmonic current, incandescent lamp, with -0.004490 coefficient value, decreases the 5th harmonic current value. The effects of each variable, mentioned above, can also be clearly seen by the aid of response surface plots (Figures 3-8).

It is obvious from Figure 3 that the harmonic current value is dependent on the both of number of heater and compact fluorescent lamp. However, the effectiveness of compact fluorescent lamp is dominant as evaluated in the Eq. (3). Figure 3 supports this idea; when the two electric heaters are used in the experiment, 3rd harmonic current value reaches up to 0.12 A. But this value gets higher than 0.12 A by using two compact fluorescent lamps instead of heaters.

Figure 3. Contour plot for the effects of the number of electric heater and compact fluorescent lamp on to the 3rd harmonic current

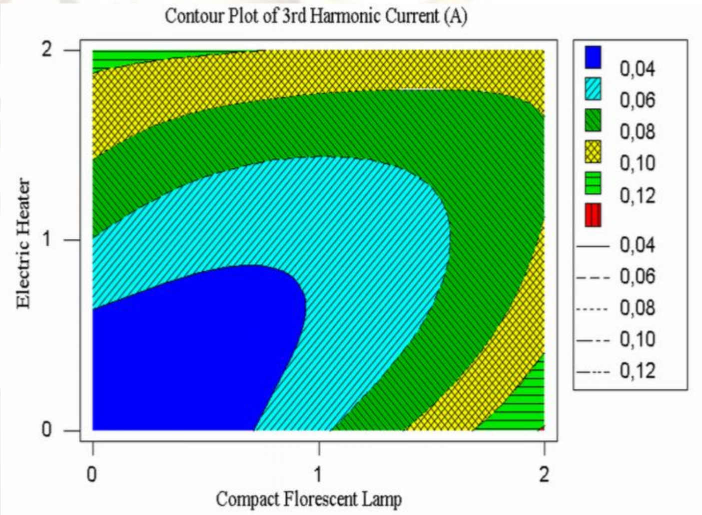
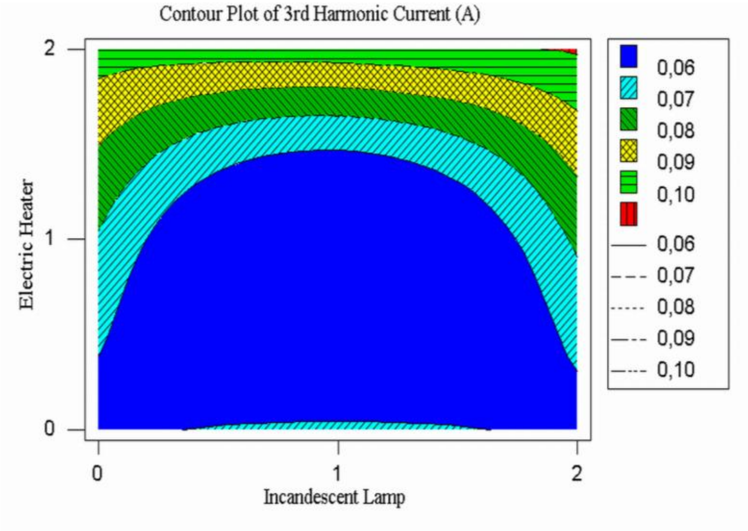


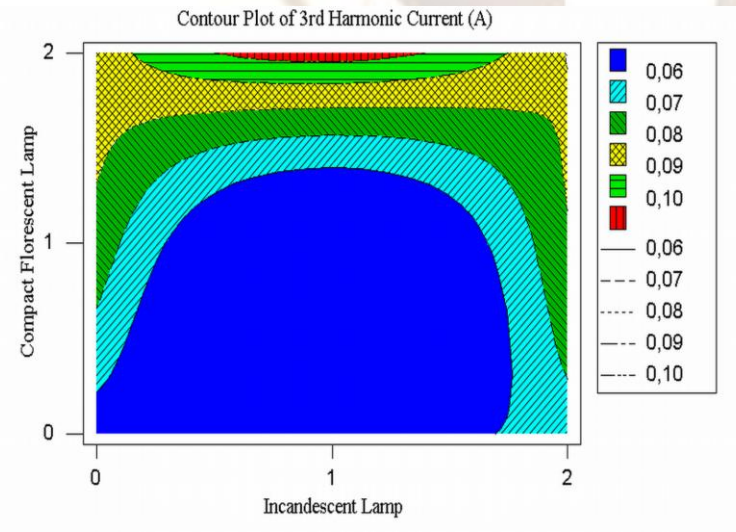
Figure 4 shows that the incandescent lamp has no significant effect unless the electric heater is included. The harmonic current value between 0.09 and 0.10 A can be reached with two electric heaters independent from the number of incandescent lamp. But the maximum value (above 0.10 A) can be achieved with the use of two incandescent lamps and two electric heaters.

Figure 4. Contour plot for the effects of the number of electric heater and incandescent lamp on to the 3rd harmonic current



The use of one incandescent lamp and two compact fluorescent lamps simultaneously causes the highest harmonic pollution (above 0.10 A). The increase in the number of incandescent lamp from one to two caused the increase in 3rd harmonic current from 0.06 A to 0.07 A without use of compact fluorescent lamp. Nearly maximum harmonic current value was achieved with use of only two compact fluorescent lamps. When the number of compact fluorescent lamp is one and less, insignificant harmonic current values can be achieved (Figure 5).

Figure 5. Contour plot for the effects of the number of compact fluorescent lamp and incandescent lamp on to the 3rd harmonic current



It is stated in equation 4 that the highest increasing affect on to the 5th harmonic current belongs to the electric heater with its +0.084519 coefficient value. Figure 6 supports this idea; while one electric heater is connected, the net harmonic current (0.12 A) does not change whether one or two compact fluorescent lamp connected to the system.

Figure 6. Contour plot for the effects of the number of electric heater and compact fluorescent lamp on to the 5th harmonic current

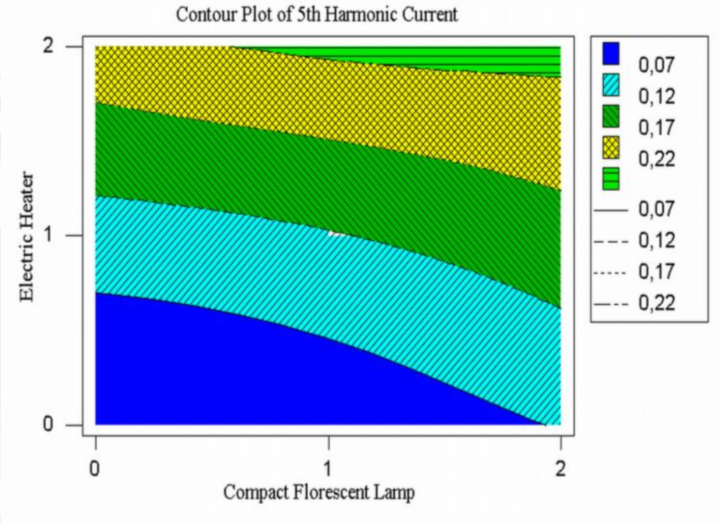


Figure 7. Contour plot for the effects of the number of electric heater and incandescent lamp on to the 5th harmonic current

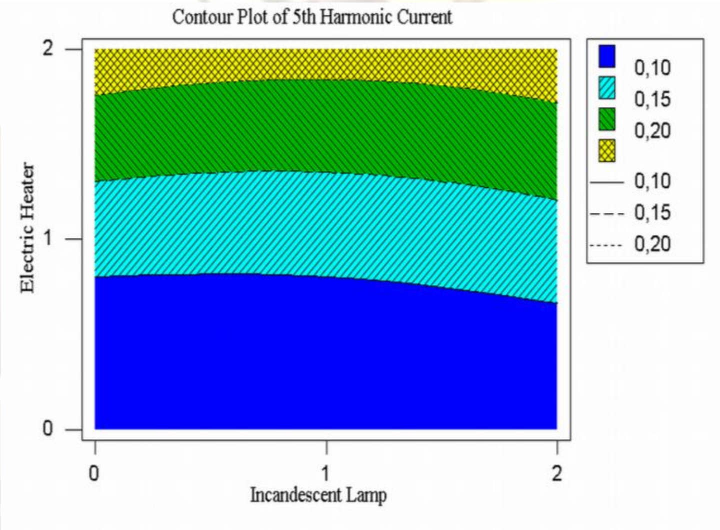
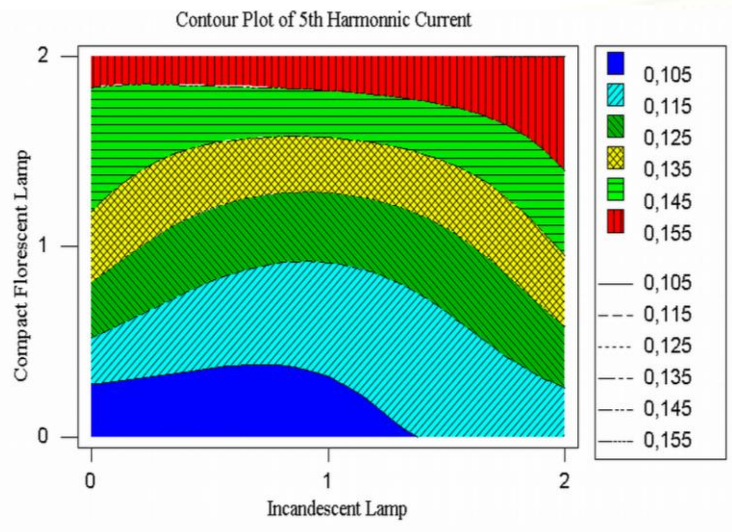


Figure 7 indicates that when the effect of heater and incandescent lamp is compared in terms of the 5th harmonic current, the increase in the number of incandescent lamp is ineffective. When two incandescent lamps are used instead of one with one electric heater, 5th harmonic current value stayed firm (between 0.10 A and 0.15 A). But, harmonic current value increased from 0.15 A to above 0.20 A when the two electric heaters are used instead of one with one or more incandescent lamp. Although less significant interaction between heater and incandescent lamp is observed, the interaction is getting more important when the use of compact fluorescent lamp is preferred instead of heater (Figure 8). This is clearly seen in equation 4 that the coefficient value of $A \times B$ and $A \times C$ is -0.008628 and -0.002900 respectively.

Figure 8. Contour plot for the effects of the number of compact fluorescent lamp and incandescent lamp on to the 5th harmonic current



IV. Conclusion

The importance of studies related with harmonics is evident when the number of new harmonic sources connected to the distribution system is taken into consideration. This study differs from the others with the point of analyzing the harmonic interaction between single-phase loads as an empirical model by the aid of three level experimental design of Box-Behnken. The results of experiments confirmed that the Box-Behnken experimental design can be used for the determination of loads responsibility and interactions of loads (A×B, A×C, B×C, etc.) for the 3rd and 5th harmonic currents. The contribution of independent variables (electric heater, compact fluorescent lamp, and incandescent lamp) to the response can be defined by just using the equations obtained as a result of the study. More than three-level of Box-Behnken experimental design can be adopted to the system harmonic analysis by using different kinds of loads and more than three loads. The other important harmonic analysis terms such as harmonic phase angle and total harmonic current distorrtion (THD) can be investigated as an independent variable like as 3rd and 5th harmonic currents for further work.

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