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# Design of Experiment (DOE) In the Improvement of the Technico-economic Indexes of H.V. Networks

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**Abstract:** The goal of this study, is to present the advantages of the design of experiments method, that consist in establishing the link between the studied physical sizes (objects functions) and their sources of variation (factors) of any process. so we had applied this method to the analysis of the powers flow process in a H.V. network with two levels of voltages while using a fractional factorial plan 2. The equation of regression (models) establish, explain a simple and efficient way, the experimental results that have been gotten on a P.4 by a software that we elaborated and perfected by Matlab version 6.5. The present work opens other multi-dimensional optimization perspectives in the electrical networks that prove to be until at the time, very complex.

**Key words:** Design expériment, objects functions, power flow, statistic, modélization

## INTRODUCTION

Classically, the management of the experimental processes by the design experiments method, is done on facilities, for which there is efficient modification of the experimental conditions[1].

The advent of the computer encouraged the use of the numeric simulations[2]; who are considered like virtual experiences (of calculation) because the studied object doesn't exist, but its behavior is informed computerly by numeric models. The scientific domain attached to the survey of the electrical networks benefitted considerably from this technical revolution, because of the convenient constraints and cost that return an impossible real experimentation. So, we tried to reproduce numerically the behavior of the electrical High Voltage (H.V.) network power flow .

With the help of the design experiments method and the modelling adopted by GAUSS-SEIDEL for the calculation of nodes voltages[2], one could establish the existing relations between some studied sizes of it (parameters of entrance) and their sources of variation X (parameters of entry or factors) as equations of regression.

Our illustration, is dedicated mainly, to the survey of the problems of regulating reactive power and voltage, in the goal to reduce the losses of power and therefore to improve the level of voltage and the capacity of network lines transportation.

## EFFECTS OF THE REACTIVE POWERS IN THE HIGH VOLTAGE NETWORKS

In high voltage, the elements of the networks are a lot more inductive than resistive[2]; it results that the voltage drop due to the exchanges of the reactive power demand, driven to non wished effects as:

- voltage drop in the network lines and the transformers.
- Supplement of the active and reactive power losses in the network lines, the transformers and the generator.
- Increase of the excitation current in the synchronous generator.
- Limitation of the transferable power in the network lines.

To compensate these effects, one can use the following means:

- To install shunt capacitor or synchronous compensators in the neighbourhoods of the reactive consumers.
- To use adjustable transformers.

It is obvious that the distribution of the reactive power that influences on the technico-economic

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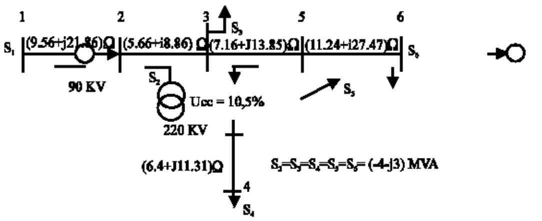


Fig. 1: Diagram of the network submitted to the analysis according to the regression model

performances depends on the rational use of the named devices.

The installation of reactive power compensator anywhere, is not justified and until now one doesn't have a precise method[3] that permits the determination of the optimal place of the compensator. This very delicate task in the complex networks can be solved by the two level factorial design, that permits to discover the degree of influence of every factor considered on the studied physical sizes.

This approach is applied at the time of the optimization, where the features of modelling are modified in order to improve the object function.

For example, we tried to establish the ties between the multi-object functions y ($V_4$, $V_6$, $I_{12}$, $I_{56}$, $\Delta P$, $\Delta Q$) and the factors X ($Q_2$, $Q_3$, $Q_4$, $Q_5$, $Q_6$, $V_1$, $K_t$) of the network in Fig. 1 and this, in the goal to optimise every response of Y

$$
\begin{aligned}
Y &= (X_1, X_2, X_3, X_4, X_5, X_6, X_7)\\
V_4 &= f(\text{ and}Q_2, Q_3, Q_4, Q_5, Q_6, V_1, K_t)\\
V_6 &= f(Q_2, Q_3, Q_4, Q_5, Q_6, V_1, K_t)\\
I_{12} &= f(Q_2, Q_3, Q_4, Q_5, Q_6, V_1, K_t)\\
I_{56} &= f(Q_2, Q_3, Q_4, Q_5, Q_6, V_1, K_t)\\
\Delta P &= f(Q_2, Q_3, Q_4, Q_5, Q_6, V_1, K_t)\\
\Delta Q &= f(Q_2, Q_3, Q_4, Q_5, Q_6, V_1, K_t)
\end{aligned}
$$

where $X_1 \div X_7$ coded Values of the real factors $Q_2 \div Q_6$, $V_1$, $K_t$

$V_4$, $V_6$ - module of the node voltage 4 and 6 in KV

$I_{12}$, $I_{56}$ - module of the network line currents 12 and 56 in KA

$\Delta P$, $\Delta Q$ -active and reactive power losses in MW and MVar

$Q_2 \div Q_5$ -consumed reactive power at the node 2 ÷ 5

$Q_6$ -produced reactive power at the node 6.

$K_t$ -transformer gain

## DESIGN OF EXPERIMENTS APPLICATIONS (DOE)

The design of experiment method permits to decrease the number of tests, by the simultaneous variation of all factors to every experience in planned combination[4,5]. The research of the influence of the factors on the variation of the response consists in fixing two values (levels) by every factor. To treat the factors in the same way (without dimension), one uses the notion of the coded values:

-1 assigned to the lower level of the factor.
+1 assigned to the high level of the factor.

The passage of the coded values X, to correspond real values Z, is expressed by the formula:

$$X_i = \frac{Z_i - Z_i^{(0)}}{(Z_i^{(U)} - Z_i^{(L)})/2}$$

Where $Z_i^{(0)}$, $Z_i^{(U)}$, $Z_i^{(L)}$ are, respectively the real values of the base; upper and lower levels of factor i.

The coded matrix of the fractional factorial design of experiments is given in Table 1, at the bottom of this table are reported the level values of the considered factors.

The number of corresponding experiments N is equal to $2^{7-3} = 16$. The signs - and + indicate respectively the lower level (-1) and the upper level (+1) of the factors.

The modelling adopted by GAUSS-SEIDEL method and the matrix calculation[2] permitted to determine the object functions corresponding to the (DOE) of Table 1. The results of observations gotten are reported in Table 2.

To analyze the results of observations corresponding to the (DOE) of the Table 1, we considered a linear regression equation as:

$$
\begin{aligned}
Y = {} & b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 +\\
& b_6x_6 + b_7x_7 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 +\\
& b_{23}\mathbf{x_2x_3} + b_{24}\mathbf{x_2x_4} + b_{34}x_3x_4
\end{aligned} \tag{1}
$$

The application of the mean square method[6,7] applied to (DOE) considering the interactions of the factors $x_ix_j$, permitted to determine the coefficients B binding every response Y to the factors X and their interactions.

$$x_8 = x_1x_2;\ x_9 = x_1x_3;\ x_{10} = x_1x_4;\ x_{11} = x_2x_3;\ x_{12} = x_2x_4;\ x_{13} = x_3x_4.$$

Under more compact matrix shape, the equation of regression (1) can be written :

$$XB = Y \tag{2}$$

The solution of the system (2) in relation to the coefficients B is given by:

$$B = \left(X^t.X\right)^{-1}.X^t.Y$$

Table 1: Design of experiment matrix $2^{7-3}$ for power flow research of the network in Fig. 1

| | $Q_2$ | $Q_3$ | $Q_4$ | $Q_5$ | $Q_6$ | $V_1$ | $K_t$ |
|---|---|---|---|---|---|---|---|
| N° of experiment | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5 = x_1x_2x_3$ | $X_6 = x_1x_2x_4$ | $X_7 = x_1x_2x_4$ |
| 1 | - | - | - | - | - | - | - |
| 2 | + | - | - | - | + | + | + |
| 3 | - | + | - | - | - | + | - |
| 4 | + | + | - | - | - | + | - |
| 5 | - | - | + | - | + | - | - |
| 6 | + | - | + | - | - | + | + |
| 7 | - | + | + | - | - | - | + |
| 8 | + | + | + | - | + | + | - |
| 9 | - | - | - | + | - | - | + |
| 10 | + | - | - | + | + | + | - |
| 11 | - | + | - | + | + | - | - |
| 12 | + | + | - | + | - | + | + |
| 13 | - | - | + | + | + | - | + |
| 14 | + | - | + | + | - | + | - |
| 15 | - | + | + | + | - | - | - |
| 16 | + | + | + | + | + | + | + |
| Level: -1 | | | 2,4 Mvar | | | 90,0kv | 0,368 |
| 0 | | | 3,0 Mvar | | | 94,5kv | 0,409 |
| +1 | | | 3,6 Mvar | | | 99,0kv | 0,449 |

Table 2: Values of the studied responses according to an exact calculation correspondent to the (D.O.E) of Table1

| $V_4$ KV | $V_6$ KV | $I_{12}$ KA | $I_{56}$ KA | $\Delta P$ MW | $\Delta Q$ MVAR |
|---|---|---|---|---|---|
| 207.9416 | 86.9732 | 96.8963 | 87.5081 | 95.6155 | 96.7853 |
| 230.6854 | 86.9732 | 96.8963 | 87.5081 | 95.6155 | 96.7853 |
| 207.0526 | 86.1907 | 95.4800 | 86.7585 | 95.7140 | 87.0196 |
| 229.4969 | 86.1907 | 95.4800 | 86.7585 | 95.7140 | 87.0196 |
| 230.5106 | 96.2253 | 85.5562 | 95.0313 | 85.4255 | 95.5250 |
| 204.0674 | 86.8655 | 0.1638 | 0.1477 | 0.1644 | 0.1631 |
| 227.4435 | 96.2253 | 85.5562 | 95.0313 | 85.4255 | 95.5250 |
| 205.2794 | 86.8655 | 0.1638 | 0.1477 | 0.1644 | 0.1631 |
| 229.4303 | 86.1907 | 95.4800 | 86.7585 | 95.7140 | 87.0196 |
| 207.1327 | 0.1478 | 0.1820 | 0.1637 | 0.1820 | 0.1552 |
| 230.1784 | 96.2253 | 85.5562 | 95.0313 | 85.4255 | 95.5250 |
| 204.0438 | 0.1478 | 0.1820 | 0.1637 | 0.1820 | 0.1552 |
| 204.8353 | 0.1820 | 0.1637 | 0.1820 | 0.1552 | 0.1478 |
| 227.8330 | 86.1907 | 95.4800 | 86.7585 | 95.7140 | 87.0196 |
| 203.8375 | 0.1478 | 0.1820 | 0.1637 | 0.1820 | 0.1552 |
| 226.7073 | 0.1820 | 0.1637 | 0.1820 | 0.1552 | 0.1478 |

## STATISTICAL VERIFICATIONS

The mathematical foundations of the D.O.E. are algebro- statistics, what gives it the capacity to manage the terms of errors to the existence of the experimental variability, the statistical analysis consists to estimate the signification of the coefficients and to verify the adequacy of the Equations[6,8,9].

To do the statistical assessment of the significance coefficients bi and $b_{ij}$ one uses the t-test of student:

$$|b_i| \geq \varepsilon = t.\delta(b) \qquad (3)$$

Where t-value of the criteria of student taken in function degree of freedom f = N - 1 and the significant level q = 0,05.

N number of experiments done

so N = 16; q = 0,05; t = f (N-1,q) = 2,131.

$\delta(b)$- Error in the evaluation of the coefficient $b_i$, $b_{ij}$.
To determinate of the error $\delta(b)$, one use the formula :

$$\delta^2(b_i) = \frac{\delta^2(Y)}{N} \qquad (4)$$

Where $\delta^2(Y)$- dispersion produced on the response Y during the process of the experiments N.

We had done virtual simulations, in this case, one can take a value of error equal[8]:

$$\delta(Y) = (0.1 \div 5)\%.b_0$$

Table 3: Equations coefficients of the model regressions

| Coefficients | Object function $V_4$ | $V_6$ | $I_{12}$ | $I_{56}$ | P | Q |
|---|---|---|---|---|---|---|
| $b_0$ | 217.2797 | 91.2231 | 0.1687 | 0.0552 | 0.3906 | 0.9097 |
| $b_1$ | -0.3740 | -0.1490 | 0.0043 | 0.0001 | 0.0141 | 0.0324 |
| $b_2$ | -0.5248 | -0.2114 | 0.0044 | 0.0001 | 0.0203 | 0.0424 |
| $b_3$ | -0.9655 | -0.2154 | 0.0045 | 0.0001 | 0.0216 | 0.0550 |
| $b_4$ | -0.5299 | -0.3028 | 0.0044 | 0.0002 | 0.0204 | 0.0428 |
| $b_5$ | 0.5180 | 0.4748 | -0.0043 | 0.0036 | -0.0151 | -0.0302 |
| $b_6$ | 11.7559 | 4.6860 | -0.0090 | -0.0028 | -0.0417 | -0.0970 |
| $b_7$ | -0.4965 | -0.0062 | 0.0001 | 0.0000 | 0.0021 | 0.0178 |
| $b_{12}$ | 0.0009 | 0.0010 | -0.0000 | 0.0000 | -0.0005 | -0.0008 |
| $b_{13}$ | 0.0315 | 0.0176 | -0.0003 | -0.0000 | -0.0029 | -0.0058 |
| $b_{14}$ | 0.0534 | 0.0117 | -0.0001 | -0.0000 | -0.0016 | -0.0041 |
| $b_{23}$ | 0.0275 | 0.0009 | -0.0000 | 0.0000 | 0.0004 | -0.0010 |
| $b_{24}$ | -0.0332 | -0.0259 | 0.0005 | -0.0002 | 0.0034 | 0.0070 |
| $b_{34}$ | 0.0190 | 0.0069 | -0.0001 | -0.0000 | -0.0001 | -0.0007 |

Table 4: Values of the responses $\hat{Y}$ calculated by the regression models

| N° of experiment | $\hat{V}_4$ | $\hat{V}_6$ | $\hat{I}_{12}$ | $\hat{I}_{56}$ | $\Delta\hat{P}$ | $\Delta\hat{Q}$ |
|---|---|---|---|---|---|---|
| 1 | 207.9416 | 86.9732 | 96.8963 | 87.5081 | 95.6155 | 96.7853 |
| 2 | 230.6854 | 86.9732 | 96.8963 | 87.5081 | 95.6155 | 96.7853 |
| 3 | 207.0526 | 86.1907 | 95.4800 | 86.7585 | 95.7140 | 87.0196 |
| 4 | 229.4969 | 86.1907 | 95.4800 | 86.7585 | 95.7140 | 87.0196 |
| 5 | 230.5106 | 96.2253 | 85.5562 | 95.0313 | 85.4255 | 95.5250 |
| 6 | 204.0674 | 86.8655 | 0.1638 | 0.1477 | 0.1644 | 0.1631 |
| 7 | 227.4435 | 96.2253 | 85.5562 | 95.0313 | 85.4255 | 95.5250 |
| 8 | 205.2794 | 86.8655 | 0.1638 | 0.1477 | 0.1644 | 0.1631 |
| 9 | 229.4303 | 86.1907 | 95.4800 | 86.7585 | 95.7140 | 87.0196 |
| 10 | 207.1327 | 0.1478 | 0.1820 | 0.1637 | 0.1820 | 0.1552 |
| 11 | 230.1784 | 96.2253 | 85.5562 | 95.0313 | 85.4255 | 95.5250 |
| 12 | 204.0438 | 0.1478 | 0.1820 | 0.1637 | 0.1820 | 0.1552 |
| 13 | 204.8353 | 0.1820 | 0.1637 | 0.1820 | 0.1552 | 0.1478 |
| 14 | 227.8330 | 86.1907 | 95.4800 | 86.7585 | 95.7140 | 87.0196 |
| 15 | 203.8375 | 0.1478 | 0.1820 | 0.1637 | 0.1820 | 0.1552 |
| 16 | 226.7073 | 0.1820 | 0.1637 | 0.1820 | 0.1552 | 0.1478 |

Table 5: Statistical analysis of the regression equations

| Parameters: object functions | t | $\delta_e^2$ | $\lvert b\rvert_{min}$ | d | $f_1$ | $f_2$ | $\delta_r^2$ | $F_c$ | $F_t$ |
|---|---|---|---|---|---|---|---|---|---|
| $V_4$ | | 0.1888000 | 0.23250 | 6 | 8 | 7 | 0.018040000 | 0.095 | 3.6 |
| $V_6$ | | 0.0332000 | 0.09760 | 5 | 9 | 6 | 0.002483000 | 0.074 | 3.4 |
| $I_{12}$ | 2.131 | 0.0000113 | 0.00180 | 5 | 9 | 6 | 0.000000950 | 0.084 | 3.4 |
| $I_{56}$ | | 0.0000012 | 0.00059 | 5 | 9 | 6 | 0.000000045 | 0.037 | 3.4 |
| P | | 0.0000610 | 0.00420 | 6 | 8 | 7 | 0.000080000 | 1.320 | 3.6 |
| Q | | 0.0003300 | 0.00970 | 6 | 8 | 7 | 0.000288000 | 0.870 | 3.6 |

The coefficients B of the regression equations whose value is superior or comparable to $\varepsilon$ are significant, therefore, the corresponding factors are considered influential.

We consider that the error of determination of the considered response doesn't exceed 2% for power losses ($\Delta P$, $\Delta Q$), currents ($I_{12}$,$I_{56}$) and 0,2% for the voltage nodes[8], in this case:

$$\left|b_i\right|_{min} = t.\frac{0{,}02 \times b_0}{\sqrt{N}}$$

$$\text{or} \left|b_i\right|_{min} = t.\frac{0{,}002 \times b_0}{\sqrt{N}}$$

After the reject of the non significant terms, we get the response values corresponding to the equations of regression $\hat{Y}$ (Table 4).

The adequacy is the degree of approximation of the experimental results and those of the models. In mathematical statistical one uses the criteria of ficher[8,9] to verify the adequacy of the model that consists mainly in comparing two dispersions: residual dispersion ($\delta_r$) and experimental dispersion ($\delta_e$):

$$F_c = \frac{\delta_r^2(Y)}{\delta_e^2(Y)}$$

Where $$\delta_r^2 = \frac{\sum_{i=1}^{N}\left(y_i - \tilde{y}_i\right)^2}{f_1} \; ; \; i = 1 \div 16$$

$$\delta_e^2(Y) = \left[(0,1 \div 5)\% \times b_0\right]^2$$

One takes $\delta_e^2(Y) = (0,002 \text{ x } b_0)^2$
for $\Delta P$, $\Delta Q$, $I_{12}$, $I_{56}$.

$$\delta_e^2(Y) = (0,002 \times b_0)^2$$

for $V_4$ and $V_6$.
The model is considered adequate if $F_c \leq F_t$
$F_t$- criteria of FISHER took according to the degrees of freedom;. $F_1$ = N-d and $f_2$ = d-1.
d- number of terms of the regression equation.
$y_i$ and $\breve{y}_i$ are respectively the values of the computation results and the model of observation i..
The indexes of statistical analysis reported in Table 5 prove the adequacy of all models ($F_c \leq F_t$).
finally the models become:

$$\begin{aligned}
\Delta P &= 0.39+0.014x_1+0.020\, x_2+0.021x_3 \\
&\quad +0.020x_4-0.015x_5-0.041x_6+0.0021x_7. \\
\Delta Q &= 0.909+0.032x_1+0.042x_2+0.055x_3 \\
&\quad +0.042x_4-0.0302x_5.0.097x_6+0.0178x_7 \\
V_4 &= 217.279-0.374x_1-0.524x_2-0.965x_3 \\
&\quad -0.529x_4+0.518x_5+11.755x_6-0.496x_7 \qquad (5) \\
V_6 &= 91.223-0.149x_1-0.211x_2-0.215x_3 \\
&\quad -0.302x_4+0.474x_5+4.68x_6 \\
I_{12} &= 0.168+0.0043x_1+0.0044x_2+0.0045x_3 \\
&\quad +0.0044x_4-0.0043x_5-0.009x_6 \\
I_{56} &= 0.052+0.0001x_1+0.0001x_2+0.0001x_3 \\
&\quad +0.0002x_4+0.0036x_5-0.0028x_6
\end{aligned}$$

## RESULTS AND DISCUSSION

The equations of regression gotten (5) are adequate with the experimental results. The analysis of this equations watch that the interactions between the factors of order two don't have an influence on the considered responses. These last depend mainly on the factors ($V_1$,$Q_2 \div Q_6$) and slightly of factor $K_t$..

However, the influence of the voltage of balance node (slack bus), has a remarkable effect on the indications technico-economic of the network. The regulating of the voltage $V_1$ (factor $x_6$) on the level (+1) permits to decrease the power losses, currents and voltage drop along the network lines, what leads to increase the capacity of line transportations; in the same way, the regulating of the reactive power loads $Q_2$,$Q_3$,$Q_4$,$Q_5$ (factors $X_1 \div X_4$) on the level (-1) and the reactive power generated $Q_6$ (factor $X_5$) on (+1) has a similar effect but weaker to the voltage $V_1$ adjusted on (+1).

The transformer gain (factor $x_7$) is slightly influential on the active losses but it is only influential on the reactive losses and voltage $V_4$.

Therefore the transformer gain participates in the reduction of the power losses and the increase of the nodes voltages, when it is adjusted on the level (-1).

## CONCLUSION

The established models permit to adjust the studied responses toward an optimal solution, satisfying the network dispatcher, to get optimal performances of the power flows in studied network, we must adjust the slack bus and reactive power generated by feeder at node number 6 on the level (+1), on the other hand, the reactive power load at the buses 1, 2, 3, 4 and transformer gain on the level (-1). These recommendations are given in decrease order of influence.

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