Experimental Design and Models of Power System Optimization and Control

R.C. BERREDO
Companhia Energética de Minas Gerais
Av. Barbacena, 1200, 30190-131
Belo Horizonte, MG
BRAZIL

http://www.cemig.com.br

P.Ya. EKEL
Pontifícia Universidade Católica de Minas Gerais
Av. Dom Jose Gaspar, 500, 30535-610
Belo Horizonte, MG
BRAZIL

http://www.pucminas.br

L.C.A. FERREIRA
Operador Nacional do Sistema Elétrico
Rua Real Grandeza, 219, 22281-900
Rio de Janeiro, RJ
BRAZIL

http://www.nos.org.br

M.V.C. MACIEL
Universidade Federal de Minas Gerais
Av. Antônio Carlos, 6627, 31270-010
Belo Horizonte, MG
BRAZIL

http://www.ufmg.br

Abstract: - This paper reflects results of research into the use of factorial experimental design for rational constructing sensitivity and functionally oriented models for system optimization and control. The questions of overcoming difficulties of statistical evaluating the results of experiments with models of systems, but not real systems are discussed. The results of the paper are of a universal character and are illustrated by applications to power engineering problems: the construction of sensitivity indices for voltage and reactive power control in power systems and functionally oriented models to evaluate power system reaction in solving problems of optimizing network configuration in distribution systems.

Key-Words: - Sensitivity Models, Functionally Oriented Models, Factorial Experimental Design, Fuzzy Logic Based Voltage and Reactive Power Control, Distribution Network Reconfigutration.

1 Introduction

The solution of many problems of power system planning and operation is based on the use of sensitivity models [1]. For example, it is possible to indicate the problem of voltage and reactive power control. The techniques for its solution (for instance, [2,3]) utilize an approach [4] allowing the use of the system Jacobian matrices to build sensitivities. However, deficient linearization accuracy permits one to use them when perturbations are small. Considering this, the paper shows the possibility to build adequate sensitivity models in a rational way on the basis of factorial experimental design [5,6].

The paper includes a brief review of experimental design as well as an example of its applying to construct sensitivities. The paper shows the use of diverse types of sensitivities for fuzzy logic based voltage and reactive power control.

A technique for evaluating experiment results consists of the stages of testing [5]: homogeneity of dispersions, significance of model coefficients, and model adequacy. These stages are common if we can perform parallel experiments in factorial space points defined by each line of the experiment matrix [5,6]. If we speak about computing experiments with a model, this circumstance has a significant impact. First of all, the impossibility to perform parallel experiments leads to estimates of output variable dispersions, which are equal to zero, and to senselessness of the first stage. Besides, testing the significance of model coefficients and model adequacy utilizes the concept of reproducibility dispersion [5] associated with the same output variable dispersions. One way around this problem is discussed in the paper.

The efficiency of using experimental design is also illustrated by constructing functionally oriented models destined, in particular, for considering power system reaction while optimizing distribution network configuration.

Many works have been dedicated to distribution network reconfiguration (for example, [7,8]). However, these works have drawbacks [9]. One of them is associated with the impossibility to consider a power system reaction: the lack of considering the change of power system losses may result to significant deterioration in reconfiguration efficiency. It demands to minimize total losses in the distribution and power systems. This statement serves for increasing the factual efficiency of solutions in distribution network reconfiguration.

2 Construction of Sensitivity Indices and Their Use for Voltage and Reactive Power Control

The evaluation of influence of the control action of regulating or compensating device j on the voltage change at bus i is associated with sensitivity S_{ij}^{V}. In the system with I controlled buses and J devices, it is necessary to have a matrix $[S_{ij}^{V}]$, $i=1,...,I$, $j=1,...,J$. As it was indicated above, constructing sensitivities in [2,3] is based on the use of system Jacobian matrices and encounters limitations. At the same time, the application of experimental design provides a means for building adequate sensitivity models. It is explained by the feasibility to build "secants", but not "tangents" [10].

The use of experimental design also permits one to eliminate from consideration actions of devices j, which have no influence on the voltage level at buses i, to evaluate the adequacy of sensitivity models and, if necessary, to change intervals of parameter varying to obtain adequate models.

Finally, the comprehensive solution [12] needs power sensitivities $[S_{kj}^{S}]$, $k=1,...,K$, $j=1,...,J$, reactive power sensitivities $[S_{kj}^{Q}]$, $k=1,...,K$, $j=1,...,J$, and loss sensitivities $[S_{j}^{\Delta P}]$, $j=1,...,J$. They can be built on the basis of the experiments used for obtaining the voltage sensitivities.

2.1 Full and fractional experimental design

The experimental design is based on varying factors on a limited number of levels. A full experiment is associated with carrying out experiments for all combinations of factor levels. It is common to use the full experiment with varying factors on two levels. It demands to fulfill 2^J experiments to construct a model

$$y = b_0 + \sum_{j=1}^{J} b_j x_j + \sum_{\substack{j=1 \\ j<q}}^{J} b_{jq} x_j x_q + \sum_{\substack{j=1 \\ j<q<r}}^{J} b_{jqr} x_j x_q x_r + \dots \quad (1)$$

It is assumed that factors can take the minimum x_j' and maximum x_j'' values and are presented in a normalized form:

$$\tilde{x}_j = \frac{x_j - x_j^0}{\Delta x_j}, \quad j=1,...,J \quad (2)$$

where $x_j^0 = 0.5(x_j' + x_j'')$ and $\Delta x_j = 0.5(x_j'' - x_j')$.

It is natural that x_j' and x_j'' correspond to -1 and $+1$, respectively. The use of the normalized factors simplifies procedures of determining coefficients of (1) and its statistical analysis. Using the normalized factors, it is possible to construct

$$y = \tilde{b}_0 + \sum_{j=1}^{J} \tilde{b}_j \tilde{x}_j + \sum_{\substack{j=1 \\ j<q}}^{J} \tilde{b}_{jq} \tilde{x}_j \tilde{x}_q + \sum_{\substack{j=1 \\ j<q<r}}^{J} \tilde{b}_{jqr} \tilde{x}_j \tilde{x}_q \tilde{x}_r + \dots \quad (3)$$

reduced to (1) as the result of substituting (2).

A matrix for the full factorial experiment with three factors is shown in Table 1.

The rule for forming experiment matrices is simple: to construct the matrix for J factors it is enough to use doubly the matrix for $J-1$ factors. In the first case, this matrix is complemented by the Jth factor on the minimum level and, in the second case, by the Jth factor on the maximal level.

Table 1. Matrix for the 2^3 design

	Factors				Factor Products				
n	x_0	x_1	x_2	x_3	$x_1 x_2$	$x_1 x_3$	$x_2 x_3$	$x_1 x_2 x_3$	y
1	+1	-1	-1	-1	+1	+1	+1	-1	y_1
2	+1	+1	-1	-1	-1	-1	+1	+1	y_2
3	+1	-1	+1	-1	-1	+1	-1	+1	y_3
4	+1	+1	+1	-1	+1	-1	-1	-1	y_4
5	+1	-1	-1	+1	+1	-1	-1	+1	y_5
6	+1	+1	-1	+1	-1	+1	-1	-1	y_6
7	+1	-1	+1	+1	-1	-1	+1	-1	y_7
8	+1	+1	+1	+1	+1	+1	+1	+1	y_8

The experimental design is based on the concept of orthogonal arrays that allows one to calculate the coefficients of (3) as follows:

$$\tilde{b}_j = \frac{1}{N} \sum_{n=1}^{N} \tilde{x}_{nj} y_n, \quad j=0,...,J, \quad (4)$$

Subsection

$$\tilde{b}_{jq} = \frac{1}{N} \sum_{n=1}^{N} \tilde{x}_{nj} \tilde{x}_{nq} y_n, \quad j=1,...,J \; (j<q), \quad (5)$$

$$\tilde{b}_{jqr} = \frac{1}{N} \sum_{n=1}^{N} \tilde{x}_{nj} \tilde{x}_{nq} \tilde{x}_{nr} y_n, \quad j=1,...,J \; (j<q<r). \quad (6)$$

Considering that $2^J > J+1$, data obtained in the full experiment have excessiveness that permits one to construct models

$$y = \tilde{b}_0 + \sum_{j=1}^{J} \tilde{b}_j \tilde{x}_j \quad (7)$$

on the basis of so-called fractional experiments.

The fractional experiment matrices may be obtained as the result of reducing a number of experiments of the full experiment in two, four, etc. times by replacing interaction effects of little significance (for instance, $\tilde{x}_1\tilde{x}_2$ in Table 1) by new parameters. The number of replacements g defines the 2^{J-g} design. For example, to construct a model

$$y = \tilde{b}_0 + \tilde{b}_1\tilde{x}_1 + \tilde{b}_2\tilde{x}_2 + \tilde{b}_3\tilde{x}_3 \qquad (8)$$

we have to perform eight experiments, although it is enough to perform four experiments in accordance with the 2^2 factorial design (four first lines of Table 1) only with $\tilde{x}_1$, $\tilde{x}_2$, and $\tilde{x}_1\tilde{x}_2 = \tilde{x}_3$.

2.2 Statistical evaluation of experimental design

As it was indicated above, the statistical evaluation based on experiments with a model encounters difficulties associated with the impossibility to estimate reproducibility dispersions. One way around this problem is the following.

Let us assume that we have a model

$$y = \tilde{b}_0 + \sum_{j=1}^{J}\tilde{b}_j\tilde{x}_j + \sum_{\substack{j=1 \\ j<q}}^{J}\tilde{b}_{jq}\tilde{x}_j\tilde{x}_q \qquad (9)$$

where $\tilde{x}_j$, $j = 1,...,J$ are considered as the central random variables with $E(\tilde{x}_j) = 0$ [12]. It leads to $E(y) = \tilde{b}_0$ and $D(y) = E\{[y - E(y)]^2\}$. If $\tilde{x}_j$, $\tilde{x}_q$, $j,q = 1,...,J$ are independent, then:

$$D(y) = D(\tilde{b}_0) + \sum_{j=1}^{J}[\tilde{b}_j^2 + D(\tilde{b}_j)]D(\tilde{x}_j) + \sum_{\substack{j=1 \\ j<q}}^{J}[\tilde{b}_{jq}^2 + D(\tilde{b}_{jq})]D(\tilde{x}_j)D(\tilde{x}_q) \qquad (10)$$

where $D(\tilde{x}_j) = D(x_j)/\Delta x_j^2$, $j = 1,...,J$.

If $D(y)$ is defined only by dispersions of the random variables, then

$$D(y) = \sum_{j=1}^{J}\tilde{b}_j^2 D(\tilde{x}_j) + \sum_{\substack{j=1 \\ j<q}}^{J}\tilde{b}_{jq}^2 D(\tilde{x}_j)D(\tilde{x}_q). \qquad (11)$$

Finally, if $\tilde{x}_j$, $j = 1,...,J$ are normally distributed in limits 0 ± 1, then considering $\tilde{x}_j \approx E(\tilde{x}_j) \pm 3\sqrt{D(\tilde{x}_j)}$, we obtain $D(\tilde{x}_j) \approx 0.11$ and

$$D(y) = 0.11(\sum_{j=1}^{J} b_j^2 + 0.11\sum_{\substack{j=1 \\ j<q}}^{J}\tilde{b}_{jq}^2). \qquad (12)$$

The second component of (12) is considerably less than the first one. It permits one to consider

$$D(y)_{rep} = 0.11\sum_{j=1}^{J} b_j^2 \qquad (13)$$

as the reproducibility dispersion which can be used to test the significance of coefficients of the models and their adequacy on the basis of the Student's test and the Fisher's test, respectively [5].

2.3 Control System

The approach to constructing sensitivity models and their statistical analysis has been implemented within the framework of the voltage and reactive power control system VRPFCS which is a module of the Energy Management System [13].

The system VRPFCS has been built on the basis of using fuzzy technology. The basic type of rules included in its knowledge base is the following:

IF	bus voltage violates the operational limit
AND	a controller is available for effective bus voltage control adjusting its output
AND	there is adequate margin of output adjustment to eliminate the restriction violation
AND	the controller is available for loss reduction (rise)
THEN	increase (decrease) the output of the controller output.

The similar rule may be presented "IF system element load is above its power capability".

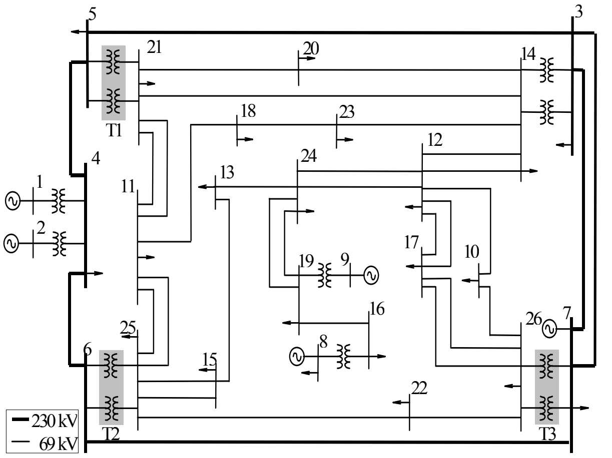
The use of this type of rules provides comprehensive and flexible solutions for different control hierarchy levels [11,13].

It is natural that the second line of the rule is associated with the use of the sensitivities S_{ij}^{V} (if the second line is "IF system element load is above its capability", then the sensitivities S_{kj}^{S} are to be applied). The third line demands the use of the sensitivities $S_j^{\Delta P}$. The utilization of other types of sensitivities for voltage and reactive power control in a deregulated environment is discussed in [14].

2.4 Illustrative example

Below is given an example of constructing the sensitivities for the subsystem of the Parana Energy Company shown in Figure 1 (bus 7 is a slack bus, and a synchronous compensator at bus 2 is out of service). The full description of initial information (line and bus data) is given in [11].

The following means may be used for control: generators at buses 1, 8, 9 and tap changing transformers T1, T2, T3. Thus, we have six control variables, and it is enough to use the 2^{6-3} design with utilizing the matrix of Table 1: generators at buses 1, 8, 9 correspond to x_1, x_2, and x_3 and transformers T1, T2, T3 correspond to $x_4 = x_1 x_2$, $x_5 = x_1 x_3$, and $x_6 = x_1 x_2 x_3$, respectively.



Figire 1. Subsystem diagram

The matrix $[S_{ij}^V]$ after the statistical analysis is given in Table 2. For comparison Table 3 includes the matrix $[S_{ij}^v]$ calculated on the basis of the approach [4]. The simulation results with these matrices show that the use of experimental design permits one to decrease an error (relative as well as sensitivity-weighted relative) in estimating the extent of control actions to a large measure.

Table 2. Sensitivities S_{ij}^v constructed on the basis of experimental design

Bus	x_1	x_2	x_3	x_4	x_5	x_6
3	0.052	0	0	0.032	-0.036	-0.047
4	0.431	0	0	0	0	0
5	0.128	0	0	0.138	0	-0.068
6	0.131	0	0	0	0.116	-0.072
10	0	0	0	-0.193	-0.232	-0.477
11	0.111	0	0	-0.418	-0.300	-0.268
12	0	0	0.089	-0.220	-0.232	-0.358
13	0.096	0	0.097	-0.234	-0.308	-0.337
14	0.086	0	0	-0.243	-0.188	-0.268
15	0.096	0	0	-0.234	-0.348	-0.328
16	0	0.368	0.455	0	0	0
17	0	0	0	-0.206	-0.236	-0.430
18	0.106	0	0	-0.372	-0.276	-0.277
19	0	0.183	0.582	0	0	-0.115
20	0.103	0	0	-0.413	-0.208	-0.256
21	0.111	0	0	-0.537	-0.220	-0.226
22	0	0	0	-0.211	-0.296	-0.469
23	0.099	0	0	-0.340	-0.248	-0.273
24	0	0	0.116	-0.220	-0.256	-0.332
25	0	0	0	-0.239	-0.400	-0.315
26	0	0	0	0	-0.228	-0.550

The described approach has also been tested on the Minas Gerais Energy Company subtransmission system. The simulation results show its high performance: it was necessary less than 4 minutes of computer (Pentium 4 1.8 GHz with RAM of 512 MB) time (with executing other tasks) to calculate all types of sensitivities for the system with 72 buses with regulating and compensating devices.

Table 3. Sensitivities S_{ij}^v constructed on the basis of the traditional approach

Bus	x_1	x_2	x_3	x_4	x_5	x_6
3	0.045	0.003	0.011	0.016	-0.016	-0.024
4	0.380	0.003	0.010	0.017	0.009	-0.024
5	0.113	0.005	0.017	0.070	-0.024	-0.038
6	0.115	0.005	0.016	-0.020	-0.059	-0.040
10	0.062	0.024	0.078	-0.095	-0.111	-0.252
11	0.094	0.020	0.063	-0.207	-0.146	-0.142
12	0.069	0.030	0.097	-0.110	-0.113	-0.188
13	0.076	0.033	0.106	-0.114	-0.150	-0.176
14	0.072	0.022	0.071	-0.123	-0.093	-0.140
15	0.081	0.028	0.089	-0.118	-0.172	-0.172
16	0.019	0.371	0.458	-0.029	-0.033	-0.048
17	0.064	0.027	0.086	-0.101	-0.111	-0.226
18	0.090	0.021	0.067	-0.190	-0.135	-0.145
19	0.024	0.183	0.585	-0.037	-0.042	-0.061
20	0.087	0.020	0.064	-0.206	-0.102	-0.132
21	0.098	0.017	0.056	-0.270	-0.106	-0.120
22	0.069	0.021	0.066	-0.099	-0.144	-0.244
23	0.085	0.022	0.069	-0.169	-0.123	-0.146
24	0.070	0.038	0.123	-0.109	-0.124	-0.180
25	0.086	0.021	0.068	-0.120	-0.197	-0.164
26	0.056	0.020	0.064	-0.083	-0.107	-0.287

3 Consideration of Power System Reaction

The direct consideration of power system reaction in distribution network reconfiguration is hampered because of a large volume of information reflecting parameters and operating modes of distribution and power systems. The questions of forming functionally oriented equivalents to evaluate power system reaction at any step of distribution system optimization are discussed below.

3.1 Increments of power losses

The power system power losses for an arbitrary step of bus load curves

$$\dot{\mathbf{J}} = \mathbf{J}_p + j\mathbf{J}_q = \begin{bmatrix} J_{p,1} \\ \dots \\ J_{p,l} \\ \dots \\ J_{p,m} \\ \dots \\ J_{p,n} \end{bmatrix} + j \begin{bmatrix} J_{q,1} \\ \dots \\ J_{q,l} \\ \dots \\ J_{q,m} \\ \dots \\ J_{q,n} \end{bmatrix} \quad (19)$$

may be calculated in the following form [1]:

$$\Delta P = 3(\mathbf{J}_p^t \mathbf{R} \mathbf{J}_p + \mathbf{J}_q^t \mathbf{R} \mathbf{J}_q) \cdot 10^{-3} \quad (20)$$

where $\mathbf{R}$ is the bus resistance matrix obtained from the bus impedance matrix $\mathbf{Y}$ by its inversion [1].

Let us suppose that we have load redistribution

$$\dot{\mathbf{J}}' = \mathbf{J}'_p + j\mathbf{J}'_q$$

$$= \begin{bmatrix} J_{p,1} \\ \dots \\ J_{p,l} + \Delta J_{p,lm} \\ \dots \\ J_{p,m} - \Delta J_{p,lm} \\ \dots \\ J_{p,n} \end{bmatrix} + j \begin{bmatrix} J_{q,1} \\ \dots \\ J_{q,l} + \Delta J_{q,lm} \\ \dots \\ J_{q,m} - \Delta J_{q,lm} \\ \dots \\ J_{q,n} \end{bmatrix} \quad (21)$$

defined by transferring a location of disconnection of the distribution network loop connecting the buses l and m. This redistribution leads to an increment of power losses

$$\delta(\Delta P_{lm}) = 3(\mathbf{J}''^t_p \mathbf{R} \mathbf{J}'_p + \mathbf{J}''^t_q \mathbf{R} \mathbf{J}'_q - \mathbf{J}_p^t \mathbf{R} \mathbf{J}_p - \mathbf{J}_q^t \mathbf{R} \mathbf{J}_q) \cdot 10^{-3}. \quad (22)$$

The transformation of (22), considering (19) and (21), leads to the following expression:

$$\begin{aligned}\delta(\Delta P_{lm}) = 3\{&(\Delta J_{p,lm}^2 + \Delta J_{q,lm}^2)(R_{ll} + R_{mm} - 2R_{lm}) \\ &+ 2[(\Delta J_{p,lm} J_{p,l} + \Delta J_{q,lm} J_{q,l})(R_{ll} - R_{lm}) \\ &- (\Delta J_{p,lm} J_{p,m} + \Delta J_{q,lm} J_{q,m})(R_{mm} - R_{lm}) \\ &+ \Delta J_{p,lm} \sum_{\substack{i=l \\ i \neq l,m}}^{n} J_{p,i}(R_{li} - R_{mi}) \\ &+ \Delta J_{q,lm} \sum_{\substack{i=l \\ i \neq l,m}}^{n} J_{q,i}(R_{li} - R_{mi})]\} \cdot 10^{-3} \quad (23)\end{aligned}$$

where R_{ll} and R_{mm} are proper bus resistances; R_{lm}, R_{li}, and R_{mi} are mutual bus resistances [1].

The load homogeneity that may take place permits one to simplify (23) as

$$\begin{aligned}\delta(\Delta P_{lm}) = 3\{&\Delta J_{lm}^2 (R_{ll} + R_{mm} - 2R_{lm}) \\ &+ 2\Delta J_{lm}[J_l(R_{ll} - R_{lm}) - J_m(R_{mm} - R_{lm}) \\ &+ \sum_{\substack{i=1 \\ i \neq l,m}}^{n} J_i(R_{li} - R_{mi})]\} \cdot 10^{-3}. \quad (24)\end{aligned}$$

The expressions (23) or (24) "prompt" the structure of functionally oriented equivalents, allowing the estimation of power system reaction without knowing proper and mutual bus resistances.

3.2 Illustrative example

Below is given an example about the construction of the functionally oriented equivalents for the subsystem of the Minas Gerais Energy Company shown in Figure 2.

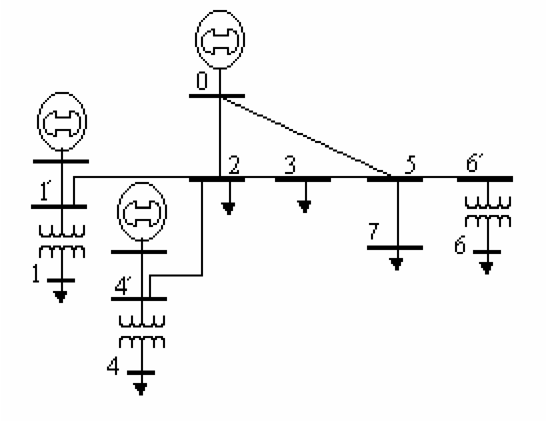


Figure 2. Power subsystem diagram

Line (138 kV) and transformer (138/13.8 kV) data are listed in Table 5. The voltage of energy supply at buses 2, 3, and 7 is 138 kV (industrial consumption).

Table 5. Line and transformer data

Line/Transformer	R (Ω)	X (Ω)
0 - 2	0.66	1.66
0 - 5	2.45	6.16
2 - 1′	2.07	5.45
2 - 3	1.30	3.31
2 - 4′	0.37	0.95
3 - 5	1.00	2.54
5 - 6′	0.38	0.95
5 - 7	0.19	0.50
1′- 1	2.41	157.33
4′- 4	2.04	150.26
6′- 6	1.04	76.74

The daily ranges of feed bus load changes with sufficient margin (20%) are the following: $16.0 \le J_1 \le 93.6$, $28.0 \le J_2 \le 165.6$, $2.4 \le J_3 \le 30.0$, $17.6 \le J_4 \le 105.6$, $23.2 \le J_5 \le 135.6$, and $17.6 \le J_6 \le 109.0$.

Let us consider, for example, the construction of $\delta(\Delta P_{1,6})$. The following factors defined by the structure of (24) are taken into account: $\Delta J_{1,6}$, $\Delta J_{1,6} J_1$, $\Delta J_{1,6} J_6$, $\Delta J_{1,6} J_2$, $\Delta J_{1,6} J_3$, $\Delta J_{1,6} J_4$, and $\Delta J_{1,6} J_5$. Considering this, it is possible to apply the 2^{7-4} fractional design matrix of Table 1.

It has been taken $0.1 \le \Delta J_{1,6} \le 2.1$ and, in this manner, $0.1 \le x_1 = \Delta J_{1,6} \le 2.1$, $1.60 \le x_2 = \Delta J_{1,6} J_1$, ≤ 195.56, $1.76 \le x_3 = \Delta J_{1,6} J_6 \le 228{,}90$, $2.8 \le x_1 x_2 = \Delta J_{1,6} J_2 \le 347{,}76$, $0.24 \le x_1 x_3 = \Delta J_{1,6} J_3 \le 63.00$, $1.76 \le x_2 x_3 = \Delta J_{1,6} J_4 \le 221.76$, $2.32 \le x_1 x_2 x_3 = \Delta J_{1,6} J_5 \le 284.76$ have been used in diverse combinations (in accordance with the 2^{7-4} design) to realize calculations of loss increments. As a result, the following model has been obtained:

$$\delta(\Delta P_{1,6}) = (-9.41 + 51.68\Delta J_{1,6} + 28.54\Delta J_{1,6}J_1 - 14.79\Delta J_{1,6}J_6 + 1.67\Delta J_{1,6}J_2 - 2.82\Delta J_{1,6}J_3 + 1.67\Delta J_{1,6}J_4 - 6.27\Delta J_{1,6}J_5)\cdot 10^{-3}. \quad (25)$$

The corresponding exact equivalent constructed with the use of proper and mutual bus resistances is the following:

$$\delta(\Delta P_{1,6}) = (21.67\Delta J_{1,6}^2 + 28.55\Delta J_{1,6}J_1 - 14.80\Delta J_{1,6}J_6 + 1.68\Delta J_{1,6}J_2 - 2.83\Delta J_{1,6}J_3 + 1.68\Delta J_{1,6}J_4 - 6.27\Delta J_{1,6}J_5)\cdot 10^{-3}. \quad (26)$$

The use of the models (25) and (26) leads to practically identical results.

4 Conclusion

An approach based on experimental design has been proposed to construct sensitivity models as well as functionally oriented models applied to system optimization and control. The line of attack on the problem of statistical evaluating the results of experiments with system models, associated with the impossibility to estimate reproducibility dispersions, has been discussed. The results of the paper are of a universal character. Their validity and efficiency have been illustrated by practical power engineering applications.

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