Experimental Design and Models of Power System Optimization and Control

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Abstract: - This paper reflects results of research into the use of factorial experimental design for rational constructing sensitivity models as well as 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: coordinated voltage and reactive power control in power systems in regulated and deregulated environments, based on fuzzy logic technology with applying diverse types of sensitivity indices, and monocriteria and multicriteria optimization of network configuration in distribution systems with constructing functionally oriented models to evaluate power system reaction.

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]. As an example, it is possible to indicate the problem of voltage and reactive power control in power systems. The techniques for its solution (for instance, [2, 3]) utilize diverse algorithmic modifications of the 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 (for example, discussion to [3]). At the same time, our experience shows that the use of experimental design [5, 6] allows one to build adequate sensitivity models in a rational way.

Taking the above into account, the present work includes a brief review of experimental design as well as an example of its applying to construct sensitivities. The work also shows the use of diverse types of sensitivities for fuzzy logic based voltage and reactive power control in power systems in regulated and deregulated environments.

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, [7-9]). However, these works have drawbacks [10]. 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 buses with regulating and compensating devices, it is necessary to have a matrix $[S_{ij}^{V}]$, $i=1,...,I$, $j=1,...,J$. As it was indicated above, the construction of sensitivities in [2-4] 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" [11, 12].

The utility of applying experimental design is also associated with the possibility to eliminate from consideration actions at buses j, which have no influence on the voltage level at buses i, that is, to take $S_{ij}^{V}=0$ (this, in a certain measure, can reduce the centralized control to the decentralized one) as well as to verify the adequacy of sensitivity models and, if necessary, to change intervals of parameter varying to obtain adequate models.

Finally, the comprehensive solution [13] needs power sensitivities $[S_{kj}^{S}]$, $k=1,...,K$, $j=1,...,J$ (reflecting the power flow change on element k due to the action at bus j), reactive power sensitivities $[S_{kj}^{Q}]$, $k=1,...,K$, $j=1,...,J$ (reflecting the reactive power flow change on element k due to the action at bus j), and loss sensitivities $[S_{j}^{\Delta P}]$, $j=1,...,J$. They can be built on the basis of the same computational experiments, which are necessary to construct the voltage sensitivities.

2.1 Full and fractional experimental design

The objective of factorial experimental design [5, 6] is to organize experiments (with a real system or its model) so as to maximize the amount of information obtained from a minimal number of experiments while simultaneously allowing a statistical evaluation of the results reliability.

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

$$y=b_0+\sum_{j=1}^{J}b_j x_j+\sum_{\substack{j=1\\ j<q}}^{J}b_{jq}x_j x_q+\sum_{\substack{j=1\\ j<q<r}}^{J}b_{jqr}x_j x_q x_r+\ \cdots\ . \tag{1}$$

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

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

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

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

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 *J*th factor on the minimum level and, in the second case, by the *J*th 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_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	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:

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

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

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

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

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

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

$$y = \tilde{b}_0 + \tilde{b}_1\tilde{x}_1 + \tilde{b}_2\tilde{x}_2 + \tilde{b}_3\tilde{x}_3 \tag{8}$$

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

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

where $\tilde{x}_j$, $j = 1,...,J$ are considered as the central random variables with $E(\tilde{x}_j) = 0$ [14]. 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

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

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

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

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

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

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

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

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 control system VRPFCS [15] which is a module of the Energy Management System [16] that functions on the basis of data obtained from the xOMNI system (software of the SCADA type) [17].

The system VRPFCS has been built on the basis of integrating traditional numerical methods with fuzzy logic technology [11-13] which is reflected by Figure 1.

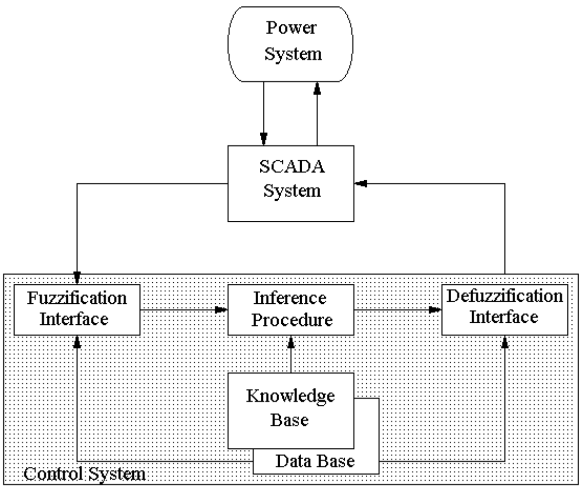

Fig.1 VRPFCS structure and its interface with SCADA system

The basic type of fuzzy rules included in knowledge base of VRPFCS 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 type of rules may be presented "IF system element load is above its power handling capability".

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

It is natural that the second line of the rule given above is associated with the use of the voltage sensitivities $[S_{ij}^V]$, $i = 1,..., I$, $j = 1,..., J$ (if the second line is "IF system element load is above its power handling capability", then the sensitivities $[S_{kj}^S]$, $k = 1,..., K$, $j = 1,..., J$ are to be considered). The third line of the rule given above is associated with applying the sensitivities $[S_j^{\Delta P}]$, $j = 1,..., J$.

The expediency of structuring the ancillary service markets into two decision stages (preparation markets and actuation markets) is justified in [18]. If structuring the ancillary service markets is associated with two stages, the control system may serve as a decision support system for managing preparation markets. In operating the actuation markets, the control system is to include a function of observing restrictions on reactive power or power factor levels for controlled elements. These restrictions may be considered as the restrictions on voltage levels, applying the reactive power sensitivities $[S_{pj}^Q]$, $p = 1,..., P$, $j = 1,..., J$ or the power factor sensitivities $[S_{pj}^{PF}]$, $p = 1,..., P$, $j = 1,..., J$, using the following type of rules:

IF	controlled element reactive power (power factor) violates the desirable reactive power (power factor) level
AND	a controller is available for effective element reactive power (power factor) control voltage control rise by 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 controller output.

However, there is another way related to the following considerations [19].

The restrictions on voltage and power handling capability are defined by technical requirements and must be observed necessarily. If the restrictions on reactive power or power factor levels (defined at the first decision stage) are related to economical considerations, they have a desirable character. It permits one to realize the consideration of the restrictions, for example, on reactive power levels on the basis of minimizing functions

$$d = \sum_{p=1}^{P} \left| Q_p - Q_p^0 \right| \qquad (14)$$

or

$$d = \left[\sum_{p=1}^{P} (Q_p - Q_p^0)^2 \right]^{0.5} \qquad (15)$$

reflecting the magnitude of reactive power deviations from their desirable levels Q_p^0.

Taking into account the essence of the problem of observing the desirable reactive power or power factor levels, it is expedient to introduce "weights" in (14) or (15). It is natural to consider Q_p^0, $p = 1,...,P$ for this goal to construct

$$d = \frac{\sum_{p=1}^{P} Q_p^0 \left| Q_p - Q_p^0 \right|}{\sum_{p=1}^{P} Q_p^0} \qquad (16)$$

or

$$d = \left[\frac{\sum_{p=1}^{P} Q_p^0 (Q_p - Q_p^0)^2}{\sum_{p=1}^{P} Q_p^0} \right]^{0,5} \qquad (17)$$

reflecting the weighted average magnitude of deviations of reactive power (WAMDRP) from their desirable levels Q_p^0, $p = 1,...,P$.

The use of (16) and (17) permits one to consider any type of restrictions $Q_p \le Q_p^0$ or $Q_p \ge Q_p^0$, $p = 1,...,P$. However, if (16) and (17) are to include only elements with $Q_p \le Q_p^0$, then it is possible to be limited by considering WAMDRP as

$$d = \frac{\sum_{p=1}^{P} Q_p^0 (Q_p^0 - Q_p)}{\sum_{p=1}^{P} Q_p^0} . \qquad (18)$$

Applying (16), (17) or (18), it is possible to realize the function of observing the desirable reactive power levels, using sensitivities $[S_j^d]$, $j = 1,...,J$. For instance, it is possible to use the following type of rules:

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 WAMDRP reduction (rise)
AND	the controller is available for loss reduction (rise)
THEN	increase (decrease) the output of the controller output.

It is natural that the use of rules of this type supposes the availability of the variable *WAMDRP Increment* and the sensitivities $[S_j^d]$, $j = 1,...,J$.

2.3 Illustrative example

Below is given an illustrative example of constructing the sensitivity indices for the subsystem of the Parana Energy Company shown in Figure 2 (bus 7 is a slack bus, and a synchronous compensator at bus 2 is out of service). The full description of initial information is given in [13].

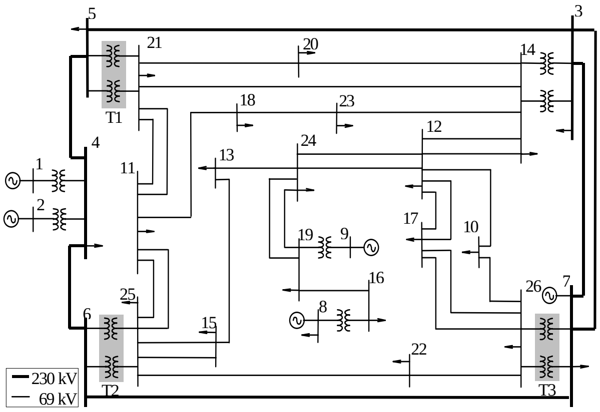

Fig.2 Subsystem diagram

The following means may be used for voltage and reactive power 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} fractional design with utilizing the matrix of Table 1: generators at buses 1, 8, and 9 correspond to variables x_1, x_2, and x_3 and transformers T1, T2, and 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.

The matrix $[S_{ij}^V], i = 1,...,26, j = 1,...,6$, after the statistical evaluation of experiment results is given in Table 2. For comparison Table 3 includes the matrix $[S_{ij}^v]$ calculated on the basis of [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 (to two and more times).

As it was indicated above, using the results of the experiments, which are necessary to construct the matrix $[S_{ij}^v]$, it is possible to obtain the sensitivities $[S_{kj}^S]$, $[S_{kj}^Q]$, and $[S_j^{\Delta P}]$ as well as $[S_j^d]$ providing the possibility to control voltage and reactive power in regulated and deregulated environments. As an example, Table 4 includes the coefficients S_{kj}^S for the most important lines.

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 approach to constructing sensitivities and their statistical analysis has also been tested on the Minas Gerais Energy Company subtransmission system. The simulation results show its high computing 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 sensitivity types for the subtransmission system (72 buses with regulating and compensating devices) on the basis of the 2^{72-65} design.

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

Table 4. Sensitivities S_{ij}^S constructed on the basis of experimental design

Line	x_1	x_2	x_3	x_4	x_5	x_6
3-5	-265.5	0	0	-464.8	0	0
3-7/1	-106.2	0	0	-89.4	74.7	135.1
3-7/2	-155.7	0	0	-130.2	109.5	196.8
4-5	-339.2	0	0	0	0	0
6-7	-83.9	0	0	0	-177.8	155.5
12-14/1	0	0	0	-28.0	33.2	87.3
12-14/2	0	0	0	-28.0	33.2	87.3
17-26/1	0	0	0	0	0	-73.7
17-26/2	0	0	0	18.3	0	-67.3
19-24/1	3.2	3.9	0	0	6.8	0
19-24/2	3.2	3.9	0	0	6.8	0

The presented above results have also been used to construct sensitivity indices in multicriteria power system operation [20].

3 Construction of Functionally Oriented Models and Their Use for Consideration of Power System Reaction in Distribution System Reconfiguration

The paper [10] reflects results related to multicriteria optimization of network configuration in distribution systems.

When analyzing models of multicriteria optimization, a vector $F(X) = \{F_1(X),...,F_q(X)\}$ of objective functions is considered, and the problem consists in simultaneous optimizing all objective functions, i. e.,

$$F_p(X) \to \min_{X \in L}, \quad p = 1,...,q \tag{19}$$

where L is a feasible region in R^n.

The lack of clarity in the concept of "optimal solution" is the fundamental difficulty in solving multicriteria problems. When applying the Bellman-Zadeh approach [21], this concept is defined with reasonable validity: the maximum degree of implementing goals serves as a criterion of optimality. This conforms to the principle of guaranteed result and provides a constructive line [22, 23] in obtaining harmonious solutions from the Pareto set [24]. Besides, the approach permits one to realize a computationally effective method of analyzing multicriteria models [25]. Finally, the approach allows one to preserve a natural measure of uncertainly in the decision process and consider indices, criteria, and constraints of qualitative character based on experience, knowledge, and intuition of a decision maker (DM).

When using the Bellman-Zadeh approach, each objective function $F_p(X), X \in L, p = 1,...,q$ is to be replaced by a fuzzy objective function or a fuzzy set

$$A_p = \{X, \mu_{A_p}(X)\}, \quad X \in L, \quad p = 1,...,q \tag{20}$$

where $\mu_{A_p}(X)$ is a membership function of A_p [21].

A fuzzy solution D with setting up the fuzzy sets (20) is turned out as a result of the intersection $D = \bigcap_{p=1}^{q} A_p$ with a membership function

$$\mu_D(X) = \min_{p=1,..,q} \mu_{A_p}(X), \quad X \in L\,. \tag{21}$$

With the use of (21) it is possible to obtain the solution X^0 providing the maximum degree of belonging to the fuzzy solution D

$$\max \mu_D(X) = \max_{X \in L} \min_{p=1,..,q} \mu_{A_p}(X) \tag{22}$$

and reduces the problem (19) to

$$X^0 = \arg\max_{X \in L} \min_{p=1,...,q} \mu_{A_p}(X)\,. \tag{23}$$

To obtain (23), it is necessary to construct membership functions $\mu_{A_p}(X)$, $p = 1,...,q$ reflecting a degree of achieving "own" optima by $F_p(X)$, $X \in L$, $p = 1,...,q$. This condition is satisfied by the use of membership functions

$$\mu_{A_p}(X) = \left[\frac{\max F_p(X) \; - \; F_p(X)}{\max\limits_{X \in L} F_p(X) - \min\limits_{X \in L} F_p(X)} \right]^{\lambda_p}. \tag{24}$$

In specific cases it is possible to use

$$\mu_{A_p}(X) = \left[\frac{\min\limits_{X \in L} F_p(X)}{F_p(X)} \right]^{\lambda_p}. \tag{25}$$

In (24) and (25) λ_p, $p = 1,...,q$ are objective function importance factors. Their forming and correcting on the basis of a procedure convenient for DM is considered in [25].

The construction of (24) demands to solve the following problems:

$$F_p(X) \to \min_{X \in L}, \tag{26}$$

$$F_p(X) \to \max_{X \in L} \tag{27}$$

providing $X_p^0 = \arg\min_{X \in L} F_p(X)$ and $X_p^{00} = \arg\max_{X \in L} F_p(X)$, respectively. The construction of (25) demands to solve only the problem (26).

Hence, the solution of the problem (19) demands analysis of $2q$+1 monocritéria problems (26), (27), and (22), respectively, or q+1 monocriteria problems (26) and (22), respectively.

Since the solution X^0 is to belong to the Pareto set $\Omega \subseteq L$ [24], it is necessary to build

$$\overline{\mu}_D(X) = \min\{\min_{p=1,..,q} \mu_{A_p}(X), \mu_\pi(X)\} \tag{28}$$

where $\mu_\pi(X) = 1$ if $X \in \Omega$ and $\mu_\pi(X) = 0$ if $X \notin \Omega$.

When analyzing problems of multicriteria optimizing network configuration in multicriteria statement, several modifications of the univariate method [26] are used to solve the problems (26), (27), and (22). The corresponding algorithms (simple search, search for an effective coordinate, search for an effective step, etc.) are flexible and easily adapted to different practical strategies in the problem solution.

The peculiarities of solving the problem (22) with the use of the algorithms indicated above consist in the following. If $X^{(m)}$ is a current point, the transition to a point $X^{(m+1)}$ is expedient if

$$(\forall p = 1,...,q): \mu_{A_p}(X^{(m+1)}) \geq \min_{1\leq p\leq q} \mu_{A_p}(X^{(m)}) . \quad (29)$$

In contrast, if

$$(\exists p = 1,...,q): \mu_{A_p}(X^{(m+1)}) < \min_{1\leq p\leq q} \mu_{A_p}(X^{(m)}) , \quad (30)$$

the transition to $X^{(m+1)}$ is not expedient. This way of evaluating the expediency of the transition to the next point $X^{(m+1)}$ leads to the solution (23) that is Pareto, if all inexpedient transitions are rejected.

In the process of optimization, as objective functions may be considered power losses, energy losses, undersupply energy, poor energy quality consumption, integrated overload of network elements, etc. in diverse combinations. As it was indicated above, the consideration of power and energy losses demands the consideration of power system reaction.

3.1. 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.

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

$$\dot{\mathbf{J}} = \mathbf{J}_p + j\mathbf{J}_q = \begin{bmatrix} J_{p,1} \\ \cdots \\ J_{p,l} \\ \cdots \\ J_{p,m} \\ \cdots \\ J_{p,n} \end{bmatrix} + j \begin{bmatrix} J_{q,1} \\ \cdots \\ J_{q,l} \\ \cdots \\ J_{q,m} \\ \cdots \\ J_{q,n} \end{bmatrix} \quad (31)$$

may be calculated in the following form [1]:

$$\Delta P = 3(\mathbf{J}_p^t \mathbf{R} \mathbf{J}_p + \mathbf{J}_q^t \mathbf{R} \mathbf{J}_q) \cdot 10^{-3} \quad (32)$$

where **R** is the bus resistance matrix obtained from the bus impedance matrix **Y** by its inversion [1].

Let us suppose that we have load redistribution

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

$$= \begin{bmatrix} J_{p,1} \\ \cdots \\ J_{p,l} + \Delta J_{p,lm} \\ \cdots \\ J_{p,m} - \Delta J_{p,lm} \\ \cdots \\ J_{p,n} \end{bmatrix} + j \begin{bmatrix} J_{q,1} \\ \cdots \\ J_{q,l} + \Delta J_{q,lm} \\ \cdots \\ J_{q,m} - \Delta J_{q,lm} \\ \cdots \\ J_{q,n} \end{bmatrix} \quad (33)$$

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

$$\delta(\Delta P_{lm}) = 3(\mathbf{J}'^t_p \mathbf{R} \mathbf{J}'_p + \mathbf{J}'^t_q \mathbf{R} \mathbf{J}'_q - \mathbf{J}^t_p \mathbf{R} \mathbf{J}_p - \mathbf{J}^t_q \mathbf{R} \mathbf{J}_q) \cdot 10^{-3}. \quad (34)$$

The transformation of (34), considering (31) and (33), leads to the following expression:

$$\begin{aligned} \delta(\Delta P_{lm}) = 3\{ & (\Delta J^2_{p,lm} + \Delta J^2_{q,lm})(R_{ll} + R_{mm} - 2R_{lm}) \\ & + 2[(\Delta J_{p,lm} J_{p,l} + \Delta J_{q,lm} J_{q,l})(R_{ll} - R_{lm}) \\ & - (\Delta J_{p,lm} J_{p,m} + \Delta J_{q,lm} J_{q,m})(R_{mm} - R_{lm}) \\ & + \Delta J_{p,lm} \sum_{\substack{i=l \\ i\neq l,m}}^{n} J_{p,i}(R_{li} - R_{mi}) \\ & + \Delta J_{q,lm} \sum_{\substack{i=l \\ i\neq l,m}}^{n} J_{q,i}(R_{li} - R_{mi})]\} \cdot 10^{-3} \end{aligned} \quad (35)$$

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 (35) as

$$\begin{aligned} \delta(\Delta P_{lm}) = 3\{ & \Delta J^2_{lm}(R_{ll} + R_{mm} - 2R_{lm}) \\ & + 2\Delta J_{lm}[J_l(R_{ll} - R_{lm}) - J_m(R_{mm} - R_{lm}) \\ & + \sum_{\substack{i=1 \\ i\neq l,m}}^{n} J_i(R_{li} - R_{mi})]\} \cdot 10^{-3}. \end{aligned} \quad (36)$$

The expressions (35) or (36) "prompt" the structure of functionally oriented equivalents.

3.2 Illustrative example

Below is given an example of constructing functionally oriented equivalents for a subsystem of the Minas Gerais Energy Company shown in Fig. 3.

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).

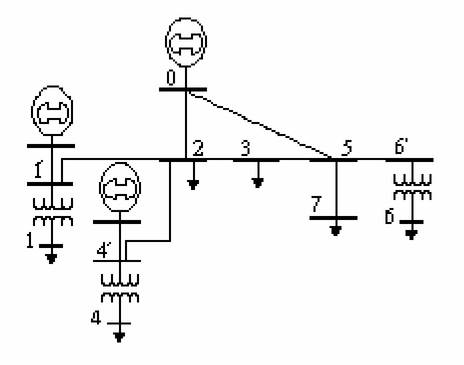

Fig. 3 Power subsystem diagram

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 $17.6 \le J_6 \le 109.0$.

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

Let us consider, for example, the construction of $\delta(\Delta P_{1,6})$. The following factors defined by the structure of (36) 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, $0.1 \le x_1 = \Delta J_{1,6} \le 2.1$, $1.60 \le x_2 = \Delta J_{1,6} J_1 \le 195.56$, $1.76 \le x_3 = \Delta J_{1,6} J_6 \le 228{,}90$, $2.8 \le x_1 x_2 = \Delta J_{1,6} J_2 \le 347{,}76$, $0.24 \le x_1 x_3 = \Delta J_{1,6} J_3 \le 63.00$, $1.76 \le x_2 x_3 = \Delta J_{1,6} J_4 \le 221.76$, $2.32 \le x_1 x_2 x_3 = \Delta J_{1,6} J_5 \le 284.76$ 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:

$$\delta(\Delta P_{1,6}) = (-9.41 + 51.68\Delta J_{1,6} + 28.54\Delta J_{1,6} J_1 - 14.79\Delta J_{1,6} J_6 + 1.67\Delta J_{1,6} J_2 - 2.82\Delta J_{1,6} J_3 + 1.67\Delta J_{1,6} J_4 - 6.27\Delta J_{1,6} J_5) \cdot 10^{-3}. \quad (37)$$

The corresponding exact equivalent is

$$\delta(\Delta P_{1,6}) = (21.67\Delta J_{1,6}^2 + 28.55\Delta J_{1,6} J_{16} - 14.80\Delta J_{1,6} J_6 + 1.68\Delta J_{1,6} J_2 - 2.83\Delta J_{1,6} J_3 + 1.68\Delta J_{1,6} J_4 - 6.27\Delta J_{1,6} J_5) \cdot 10^{-3}. \quad (38)$$

The use of the models (37) and (38) 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.

5 Acknowledgments

This research was supported by the National Council for Scientific and Technological Development of Brazil (CNPq) – grant 302406/ 2005-0, and Energy Company of Minas Gerais (CEMIG) – contract 4570007701.

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