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Identification of Synchronous Machine Parameters Using Constrained Optimization

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Abstract – In order to investigate transient performance problems in isolated power systems an accurate system dynamic model is required. Real measurements, under specific system operational conditions, have been used for the identification of the conventional generator unknown parameters. Frequency and power variations, resulting from the simulation model using the estimated parameters, are compared with the frequency and power deviations, measured during the corresponding real operational conditions in order to demonstrate the successful performance of the proposed methodology.

Index Terms – Isolated Power System, System Simulation, Dynamic Models, Parameters Identification.

I. INTRODUCTION

The importance of obtaining accurate parameters of synchronous machines is ever increasing because of the increased power system capacity, especially for autonomous power systems. System stability analysis becomes very critical, and suitable models are needed with accurate system parameters. Due to the complicated non-linear phenomena of saturation and eddy currents of the generator, the selection of a proper model and the determination of the associated parameters is challenging and stimulating to the engineers and researchers in the power area.

Many methods had been developed and applied to measure the parameters [1-3]. All of these methods are conducted under off-line conditions and under various load conditions. This paper presents the application of constrained optimization method for the identification of the dynamic synchronous machine parameters.

Because of the lack of sufficient information, a procedure of real time measurements took place by the Greek Public Power Corporation (P.P.C.), at the Crete island power system on November 1997. The results of these measurements, which are presented in the next paragraph of this paper, are used for the identification of the governor and the electromechanical unit dynamic models parameters.

Based on these measurements the governor and the generator parameters were estimated using an innovative non-linear programming approach, described in the appendix of the present paper. These estimated parameters are used in the following for the investigation of the dynamic behavior of medium size isolated power systems with thermal units and WTs, using the EUROSTAG software, [4]. This investigation aims to define operating rules for increasing the wind power penetration in islands without deteriorating their dynamic security.

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II. PRESENTATION OF THE POWER SYSTEM

The considered power system is the power system of the Crete island, which is the largest Greek Island. It provides a good case study for illustrating the different operating features of large isolated systems and the security assessment studies that should be conducted. The main features of the system are the following:

A. It is a purely thermal power system that consists of 64 bus-bars, 20 generator (PV) buses, 11 wind power generator buses and 33 load (PQ) buses. The conventional generation system consists of two major power plants having four different types of generating units. These plants are located near to the major load demands at the central and the west area of the island. A third oil plant is planned to be installed at the east side of the island in order to provide a better distribution geographically of the power production. There are twenty conventional generating units in total, which are all oil-fired units. A briefly presentation of the units' types are shown in Table 1.

	No. of Machines	Nominal Power (MW)
Steam	6	103.5
Diesel	4	48
Gas	7	185
Comb.Cycle	1+2	132
W.T.	138	81.7
Total	158	550.2

Table 1: Crete Power System Generators.

B. The system peak load is equal to 360 MW while the active power losses have been calculated to be 4MW. This means that there is a reserve generating capacity of 104.5 MW, which is about 29% of the system load demand and losses. The transmission network consists mainly of 150 kV circuits and, to a less extent, of 66 kV circuits. The annual peak load demand occurs on a winter day and overnight loads can be assumed to be approximately equal to 25% of the corresponding daily peak loads.

C. The thermal-steam and diesel units mainly supply the base-load, while the combustion turbines supply the daily peak load or the load that cannot be supplied by the other units in outage conditions. These units have a high running cost, which increases significantly the average cost of electricity being supplied. A control center located in one of the most important system substations supervises the generation system and the transmission network.

D. All the wind parks, with few exceptions, are installed at the eastern part of the island that presents the most favorable wind conditions, while they are connected to the grid through HV/MV substations of 20kV/150kV. As a result, in case of faults on some particular lines, the majority of the wind parks will be disconnected. Furthermore, the protections of the WTs might be activated in case of frequency variations, decreasing additionally the dynamic stability of the system. Thus the necessity of a precise simulation model of the complete isolated power network in order to perform accurate and realistic transient performance analysis is of great importance for the security assessment of the isolated power network.

III. Power System Field Measurements

The dynamic response of the conventional units to sudden changes of the load and the frequency variations depend critically on the parameters of the corresponding speed governors. The precise values of these parameters were unknown in case of Crete power system. Therefore the Public Power Corporation (PPC) of Greece performed field measurements on Crete power system in order to gather sufficient information for these parameters identification, [5]. The transient behavior of the system was recorded in computers equipped with A/D converter cards. They were installed at the power station respectively, in order to record the active power response of the thermal units and the frequency deviation of each generator. Three "test" disturbances were realized, while the total duration of each recording was 3 min. The recorded disturbances were conventional synchronous machine rejection, which took place under different operating conditions, involving high and low load period (Fig.1).

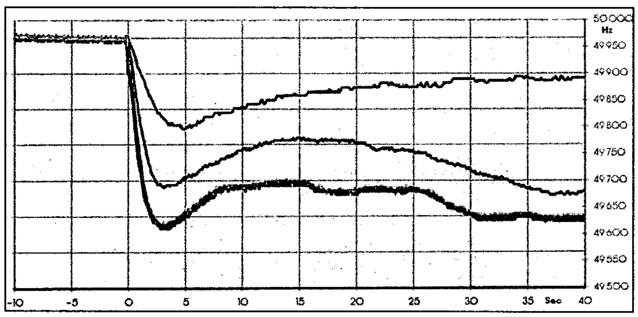

Fig. 1: Frequency deviations of the system in three disturbances.

Based on these measurements, the governor parameters were estimated, following the constrained optimization method, while the power system dynamic was simulated, as the next paragraph describes.

IV. Dynamic Model of The Power System

The models, which are used for the presentation of the system components were chosen by taking into account that the duration of the transient phenomena under consideration are between 0.1 and 10 sec approximately. The equations for the main components of the system are as following, [6]:

a. Diesel motors and Gas turbines.

The generic model, illustrated in Fig. 2, is used for the simulation of the diesel engines and the gas turbines speed governors including the electromechanical unit:

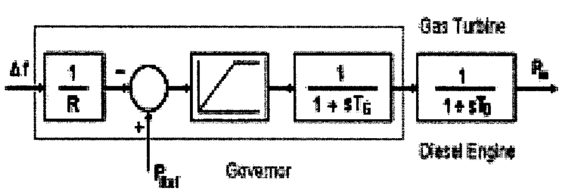

Fig. 2: Diesel or Gas unit speed control and turbine dynamic model.

where: Δf, is the per unit frequency change (f_o=50Hz).
Pm, is the mechanical power produced by the diesel engine or by the gas turbine.
R, is the droop of the speed governor.

Input is the frequency change and output is the produced mechanical power, while the diesel engine or the gas turbine electromechanical system is represented by a first order lag with a time constant T_D. T_G is the time constant of the hydraulic actuator of the governor mechanism.

b. Steam unit.

The block diagram of figure 3 represents the speed governor system including the corresponding electromechanical part for each steam unit.

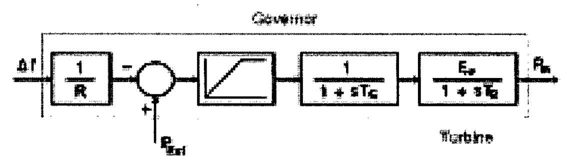

Fig. 3: Steam unit speed control and turbine dynamic model.

where: Δf, is the per unit frequency change (f_o=50Hz).
Pm, is the mechanical power of the steam turbine.

The transfer function for the governor includes the speed relay. The steam turbine is represented as a single type model whose transfer function is:

$$G(s) = F_{HP} / 1+sT_R$$

where: F_{HP}, is the fraction of total turbine power generated by the high-pressure section. Here F_{HP} is equal to one because only one high-pressure state exists.

An integral control device also exists for the elimination of the steady state error after disturbances; thus it is added in parallel to the machine droop device of the speed controllers in Fig.1 and Fig.2, as it is shown in figure 4.

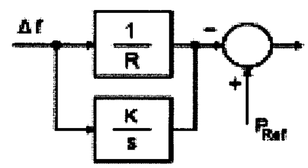

Fig. 4: Addition of the integral control block.

c. Voltage regulator.

The standard DC1 model of IEEE is considered for the voltage regulator of each generator of the system [6].

d. Asynchronous generator equations.

Wind generators are simulated as induction machines with a sort-circuited double cage rotor. These induction machines are derived from synchronous machines, with the excitation winding short-circuited. Besides this, the machines are assumed to be perfectly symmetrical [1,3,5].
The initial slip corresponds to the intersection of the electrical torque curve and the opposing mechanical torque.

The mechanical torque is a linear function of the asynchronous wind generator speed:

$$P_m = T_m . \omega_r$$

e. Load equations.

In general, power system loads are composed of a variety of electrical devices. For resistive loads, such as lighting and heating loads, the electrical power is independent of frequency. In case of motor loads, the electrical power changes with the frequency due to changes in motor speed. The overall frequency dependent characteristic of a composite load may be expressed as:

$$\Delta P_e = \Delta P_L + D_i \Delta f$$

where: ΔP_L, is the non frequency sensitive load change
$D_i \Delta f$, is the frequency sensitive load change
D_i, is the load damping constant

In the absence of a speed governor, the inertia constant and the damping constant determine the system response to a load change. The steady state speed deviation is such that the change in load is compensated by the variation in load due to frequency sensitivity.

V. Parameters Identification using Field Measurements

The first two recorded disturbances, which were realized as it has mentioned in paragraph 3, were used in order to supply input data for the identification procedure, while the last one was used for evaluating purpose.

Mathematical formulation of the identification problem of a power system

Lets consider the mathematical model of a power system described by the mathematical relation between inputs-outputs after the integration of the system state space equations and with assumed topology but with unknown system parameters, [8, 9, 10, 11] i.e.:

$$\boldsymbol{y}(t) = g(\boldsymbol{a}(t), \boldsymbol{x})$$
$$\boldsymbol{x}_l \leq \boldsymbol{x} \leq \boldsymbol{x}_u$$

where: $\boldsymbol{y}$ is the N-dimensional vector of the power system outputs
$\boldsymbol{a}$ is the an m-dimensional vector of the power system inputs,
$\boldsymbol{x}$ is the n- dimensional vector of the power system dynamical model unknown parameters, which are constant.

The power system identification problem consists determining the system unknown parameters, $\boldsymbol{x}$, in such a manner that the deviation between the model and the real system responses to the same class of inputs, $\boldsymbol{a}$, is minimized. The degree of goodness of fit is represented by the value of a predefined error norm $f(\boldsymbol{x})$. Given that T (t=1,...,T) discrete observations are made on the real power system input $a = \Delta P_L$ (the load change to the power system), and the corresponding system outputs are given by $y(t) = (\Delta P_{G1}(t),\dots,\Delta P_{GN}(t), \Delta f(t))$ (where ΔP_{Gi} the output power change of the i^{th} generation unit and Δf the change of the power system frequency), and the least-squares norm is employed, then the power system identification problem can be expressed in the form (see figure 5):

$$\underset{x}{Minimize}\ f(\boldsymbol{x}) = \sum_{t=1}^{T}\sum_{j=1}^{N}\left(y_j^t - \hat{y}_j^t\right)^2$$

subject to the constaints:

$$hpf_l \leq hpf \leq hpf_u \qquad (1)$$
$$R_{il} \leq R_I \leq R_{iu}$$
$$T_{Gil} \leq T_{Gi} \leq T_{Giu}$$
$$T_{Til} \leq T_{Ti} \leq T_{Tiu}$$

where $\boldsymbol{x}$ are the decision variables of the above optimization problem (1), i.e. $\boldsymbol{x} = (hpf, R_i, T_{Gi}, T_{Ti})$, ($hpf$ is the system inertia, R_i is the droop of the unit i, T_{Gi} and T_{Ti} are the generator and turbine time constant of the unit i respectively), y^t and $\hat{y}^t$ are known values of the output of system and model respectively, at time instants t, t=1,...,T. In the identification problem of the particular power system of the Crete island the constraints are :

$$50 \leq hpf \leq 250$$
$$0.05 \text{ sec} \leq T_{Gi} \leq 0.5 \text{ sec}, \forall i$$
$$1 \text{ sec} \leq T_{Ti} \leq 3 \text{ sec, for steam units} \qquad (2)$$
$$0.5 \text{ sec} \leq T_{Ti} \leq 1.5 \text{ sec, for gas units}$$
$$1 \text{ sec} \leq T_{Ti} \leq 2 \text{ sec, for diesel units}$$
$$R_i > 0$$

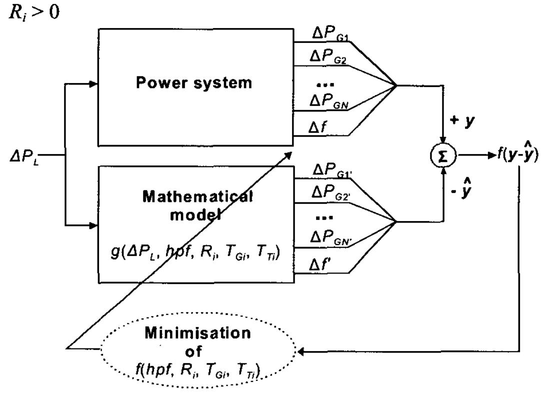

Fig. 5: Block diagram of the parameter estimation procedure.

The effect on the real power system after a step input changing (ΔP_L) is observed directly at the output $\boldsymbol{y}^t$, and the set of the parameters estimated values is used to develop the mathematical model. The responses to the same input from the mathematical model, $\hat{\boldsymbol{y}}^t$, are then used to formulate the criterion. In this problem, the sum of squared residuals between experimental data and numerically integrated solutions of the differential equations is formulated. The parameters are then systematically varied by the minimization procedure described in the Appendix, so as to locate the minimum of the error surface respecting at the same time the imposed constraints [9, 10, 11].

Unit Name	T_G (sec)	T_D (sec)	Droop (Hz/MW)
Diesel 1	0.070	0.8062	0.0538
Diesel 2	0.070	0.8062	0.0538
Diesel 3	0.070	0.8062	0.0538
Diesel 4	0.070	0.8062	0.0538
Steam 1	0.131	1.446	0.1891
Steam 2	0.109	1.422	0.1602
Steam 3	0.109	1.422	0.1602
Steam 4	0.072	1.262	0.1421
Steam 5	0.072	1.262	0.1421
Steam 6	0.072	1.262	0.1421
Gas 1	0.0783	0.5656	0.0550
Gas 2	0.0783	0.5656	0.0550
Gas 3	0.0806	0.6564	0.0723
Gas 4	0.0706	0.7259	0.0656
Gas 5	0.0686	0.6560	0.0619
Gas 1 ©	0.0581	0.5763	0.0564
Gas 2 ©	0.0581	0.5763	0.0564
Steam 1 ©	0.0880	1.2229	0.0957

Table 2: Each Generators Control Parameters.

By applying the parameter identification procedure indicated in figure 5 for the dynamic power system model of the Crete island, the values of table 4 have been obtained.

VI. Evaluation Results and Discussion

The power system of Crete was simulated using the EUROSTAG software, considering the dynamic models of the system, as they were described in paragraph 4. The initial operation profile of the simulations, was determined taking into account the conducted third test power profile, while the disturbances was the disconnection of a conventional unit that was generating 19MW. The calculated values from the previous study of units' droops and time constants were used for the description of the controllers.

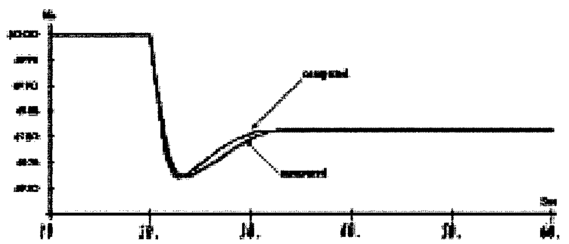

Fig. 6: System frequency deviation corresponding to a 10MW step loss, measured and simulated.

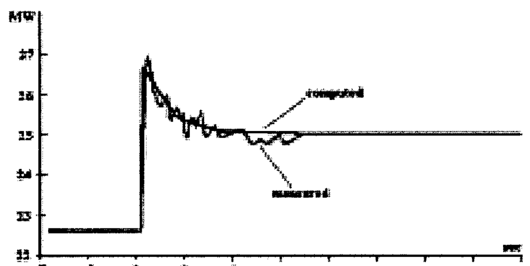

Fig. 7: Four Diesel units power change in total, corresponding to a 10MW step loss, measured and simulated.

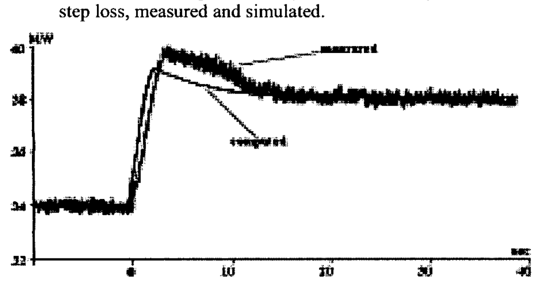

Fig. 8: Three steam units power change in total, corresponding to a 10MW step loss, measured and simulated.

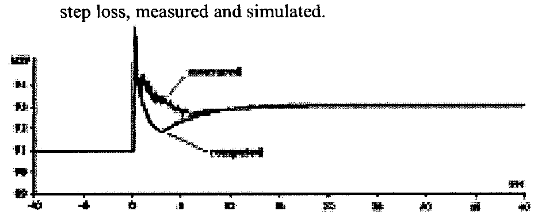

Fig. 9: Five gas units power change in total, corresponding to a10MW step loss, measured and simulated.

The comparison of the dynamic behavior of the system, derived through simulation that is using the estimated governor and turbine dynamic model parameters and the corresponding measured curves by P.P.C. during the test disturbances, is represented in figures 6-9.

It is obvious that the previous diagrams, where the estimated parameters of the power generating unit's dynamic models have been used, are very satisfactory, compared with the measured ones during the performed tests.

VII. Conclusions

In this paper, a method for the identification of conventional generator parameters in a medium size isolated power system is presented. The results of the method are based on real time system dynamic behavior measurements.

Frequency and generated power variations resulting from the simulation model, using the estimated parameters, are compared with the results of a second independent group of real time measurements. Regarding the previous shown diagrams, the comparison of the results indicates very satisfactory parameter estimation.

It is found that it is possible to identify, with sufficient accuracy, the parameters that characterize any conventional synchronous machine dynamic model, when analytical field measurements have been realized, using constrained optimization.

Concluding, the system model, with the estimated parameters, simulates with accuracy the dynamic performance of the isolated power system, giving the ability for better, analytical and reliable studies.

VIII. Acknowledgments

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References

[1] M.Papadopoulos, P.Malatestas, N.Hatziargyriou, "Simulation and Analysis of Small and Medium Size Power Systems Containing Wind Turbines," IEEE Trans. on Power Systems, Vol.6, Nr.4, Nov.1991.

[2] E.N.Dialynas, N.D.Hatziargyriou, N.C.Koskolos, E.S.Karapidakis, "Effect of High Wind Power Penetration on the Reliability and Security of Isolated Power Systems," paper 38-302, CIGRE 1998 Session, 30th August - 5th September, Paris.

[3] N.Hatziargyriou, M.Papadopoulos, "Consequences of High Wind Power Penetration in Large Autonomous Power Systems," CIGRE Symposium, Neptun, Romania, 18-19 Sept.1997.

[4] Eurostag 2.3, Package, User's Guide. Date

[5] N. Hatziargyriou, E. Karapidakis, D. Hatzifotis, "Frequency Stability of Power Systems in large Islands with high Wind Power Penetration," Bulk Power Systems Dynamics and Control Symposium – IV Restructuring, Santorini, August 24-28, 1998.

[6] Prabha Kundur, "Power System Stability and Control", Electric Power Research Institute.

[7] D.M. Himmelblau, "Applied Nonlinear Programming," McGraw-Hill, New York, NY, 1972.

[8] Moukarzel I. K. Dubouix P. and Vidallon C. M., 1985. Combined simplex and gradient approximation method for least Pth optimization. Proc. International Congress for Statistics, Computer Sciences, 30 March-4 April, Nenoufia, Egypt, 385-390.

[9] Reklaitis G.V., Ravindran A, and Ragsdell K.M., 1983. Engineering optimization methods and applications. John Willey & Sons, New York.

[10] Vidallon C. M. and Moukarzel I. K., 1986. Automated penalty method for circuit performance optimization without calculating derivatives. Proc. IASTED International Symposium. Modelling, Identification and Control, 18-20 Febr. Innsbruck Austria, 67-70.

[11] Nedler J.A. and Mead R., 1965. A Simplex method for function minimization. The Computer Journal, 7, 308-313.

[12] Dimopoulos I., 1988. Etude de diverses méthodes de détermination des valeurs optimales applicables en Biologie et en Ecologie. Thèse de Doctorat, Université Paul-Sabatier, Toulouse, France.

[13] D.J. Trudnowski, J.C. Agee, "Identifying a Hydraulic-Turbine Model From Measured Field Data," IEEE Trans. on Energy Conversion, Vol.10, No.4, December 1995.

[14] Toshio Inoue, Haruhito Taniguchi, Yasuyuki Ikeguchi, Kiyoshi Yoshida, "Estimation of Power System Inertia Constant and Capacity of Spinning Reserve Support Generators Using Measured Frequency Transients," IEEE Trans. on Power Systems, Vol.12, No.1, February 1997.
[15] X. Xu, R.M. Mathur, J. Jiang, G.J. Rogers, P. Kundur, "Modeling of Generators and Their Controls in Power System Simulations Using Singular Perturbations," IEEE Trans. on Power Systems, Vol.13, No.1, February 1997.
[16] D.J. Trudnowski, J.C. Agee, "Parameters Identification of Power System Generators," IEEE Trans. on Power Systems, Vol.10, No.4, December 1999.
[17] Zhengming Zhao, Fungshi Zheng, Jide Gao, Longya Xu, "A Dynamic On-line Parameter Identification and Full-Scale System Experimental Verification for Large Synchronous Machines," IEEE Trans. on Energy Conversion, Vol.10, No.3, September 1995.

APPENDIX

The constrained optimization problem discribed by eqs (1) involves locating levels of x that produce an optimal response in $g(a,x)$ such that the constraints of the problem are not violated. For the solution of this optimization problem, a two step procedure were used :

a. *the grid search*

The grid search is used to find the global minimum when the objective function f possesses several relative minimum points. In this step, the constraints range defined by eqs (2) is divided for each parameter into a grid of specific size and it is methodically searched. The range of each unknown variable x_i in the problem (1) can be divided in n_i equal intervals, thus $n_1.n_2.\dots.n_n$-dimensional rectangles are formed. The value of f is calculated in the center of each rectangle. The k best centers of these rectangles are used as beginning values for the local optimizations effectuated by a modified version of the non-linear simplex method [9,13]. This method is efficient as a first step of the optimization procedure in order to detect the region where the global minimum is likely to be found. Once this region is found, the more efficient technique of non-linear simplex is used to find the precise location of the global minimum point [9,13].

b. *the modified non-linear Simplex method*

The non-linear simplex method used here was initially developed by Nedler and Mead, 1965, [12]. The simplex procedure derives its name from the geometric figure formed by a set of n+1 points in the n-dimensional space of the unknown parameters (decision variables). The basic idea in the non-linear simplex method is to compare the values of the objective function, f, at the n+1 vertices of a simplex and to move this simplex gradually towards the optimum point during the optimization process. The method approaches the optimum in stepwise fashion by moving away high values of the objective function rather than by moving in a line toward the minimum. It is a so-called "direct" procedure in that no derivatives of the objective function are required. For this reason it is readily applicable to situations which are analytically difficult, as the parameters identification problem of a dynamic model. The theoretic mathematical details of the simplex method are discussed extensively in [8, 10, 12] Thus, only a brief general outline of simplex procedure is given here.

The objective function is evaluated at each vertex and an attempt to form a new simplex by replacing the vector with the greatest value of the objective function by another point is made. The adaptive feature of the approach enables the simplex to reflect, extend, contract, or shrink so as to conform to the characteristics of the response surface.
Mathematicaly, the reflected point x^r is given by
$x^r = (1+a)x^c - ax^s$, $a > 0$,
the expanded point x^e is given by
$x^e = \gamma x^r + (1-\gamma)x^c$, $\gamma > 1$,
and contacted point x^k is given by
$x^k = \beta x^s + (1-\beta)x^c$, $0 \le \beta \le 1$

where x^s is the vertex corresponding to the worst cost function value i.e. $(f(x^s) = max[f(x^i)], \forall i)$,
x^b is the vertex corresponding to the best cost function value $(f(x^s) = min[f(x^i)], \forall i)$ and the "centroid" point is calculated by $x^c = \sum_{i=1}^{n} w_i x^i$, $i \neq s$, with $w_i = 1/n$

Any trespassing by the progressing simplex over the border of a constraint will be followed automatically by contraction move which will eventually keep the progressing simplex inside the constraints range.

The improvement of the basic procedure described above, involves some modifications such as [8, 10, 12]:

a. If a reflection process gives a point x^r for which $f(x^r) < f(x^b)$, then we replace the expansion by an one-dimensional search along the direction $(x^r - x^c)$ (we replace x^e by x^{ed} such that $f(x^{ed}) = \underset{\lambda}{Min}\, f(x + \lambda(x^r - x^c))$.
b. Before the shrinkage of simplex, a quadratic interpolation is made using the three vertices with the lowest values of the objective function.
Lets x_1, x_2 and x_3 the three points and f_1, f_2, f_3 the corresponding values of the objective function. The new point is given by

$$x = \frac{f_1(x_1^2 - x_3^2) + f_2(x_3^2 - x_1^2) + f_3(x_1^2 - x_2^2)}{2(f_1(x_2 - x_3) + f_2(x_3 - x_1) + f_3(x_1 - x_2))}$$

c. In the place of the habitually used "centroid" point, which attribute the same weight at each vertex, we use w_i which the values are inversely proportional to the values of $f(x^i)$ (if $x^i \neq x^j$ with $J(x^i) \le J(x^j)$ we use $w^i \ge w^j$ with $\sum_{i=1}^{n} w_i = 1$). Thus, the centroid is placed nearest to the vertices with the better values of $f(x)$

Finally two criterions to stop the procedure are considered. The procedure will progress towards the optimum point as long as the simplex is not collapsed into its centroid. We assume convergence of the process whenever the following two conditions are satisfied:

a. The simplex shrinks to a specified small size, i.e., the distance between any two vertices among $x^1, x^2, \dots, x^{n+1}$ becomes smaller than a prescribed small quantity, ε_1.

b. The standard deviation of the objective function value becomes sufficiently small, i.e. when

$$\sqrt{\frac{\sum_{i=1}^{n+1}(f(x^c) - f(x))^2}{n+1}} \le \varepsilon_2$$

where $\varepsilon_2 > 0$ is a specified small number.

The method presented in this paper and used for the power system identification problem does not require the derivatives of the objective function to find the minimum point, thus it is very appropriate to the solution of the constrained minimization problem (1). No assumptions are made about the objective function surface except that it is continuous. The problem of false convergence at a point other than the global minimum, encountered by almost all the minimization methods, and the problem of the presence of various local minima are resolved inherently, using the proposed exhaustive grid search in the first step of the optimization procedure.