SYSTEM LOAD PARAMETER ESTIMATION USING PASSIVE EXPERIMENTAL TESTS

MOGA M.*, MOLNAR-MATEI F.*, IOVAN M.**
* "Politehnica" University of Timişoara, bd. V.Parvan, no.2,
**Continental Automotive Romania, Calea Martirilor, no.2,
mihai.moga@et.upt.ro, florin.molnar@et.upt.ro, iovanmonica@yahoo.com

Abstract – This paper presents a software application designated to identify system loads using passive tests performed on the basis of monitored data. In this context, the system load is defined as mix of a static and a dynamic component. For each component was developed appropriate load model, therefore the static component was considered a simple model, represented by constant impedance, but for dynamic component, the load model represents an equivalent induction motor, described by an input-state-output mathematical model. Using these load models was developed a procedure for estimation their parameters by processing information recorded by digital monitoring devices placed in the distribution substations. To validate the developed procedure in this paper further are presented some comparisons between responses given by simulated load (with the previously estimated parameters) and responses recorded on real load for same input signals.

Key words: System load, parameters estimation, load model

1. INTRODUCTION

The importance of accurate representation of the power system components has been widely recognized for several decades both for system stability analysis and voltage stability, especially concerned in the deregulated market environment. The models for many system components, such as generators, transformers, transmission lines, regulators, are today of a high level of accurateness and well established. Not the same can be said about load, as an important component of the power system, although the importance of its modeling in system simulations is well recognized [1], [2].

The term "load" is defined by [1] as a portion of system that is not explicitly represented in a system model, but rather is treated as a single power-consuming device connected to a bus in the system model. So the term load in this context can include more individual components as electric motors, lighting devices, heaters, shunt capacitors, step-down transformers, distribution feeders, etc. As the load composition can change in a random mode, developing of an accurate load mathematical model became a challenge and a difficult task, due its complexity and its uncertainty.

The simplest load model is the static model that expresses the active and reactive powers at any instant of time as function of the bus voltage magnitude and frequency at the same instant. As static load model, traditionally power system analysis tools often use the constant impedance, constant current, or constant power load model. Due to dominant power consumption in electric machines, with a dynamic behavior during system transients, this load model proved to be inadequate for power system analysis [1]. Consequently, for transient stability studies it is recommended to use a dynamic load model or a combination of static and dynamic load model [3]. This approach is a recent trend and many works developed load models in this manner [4], [5]. Third-order induction motor models are often used for dynamic load part [2]. Consequently, this paper will consider such a load model as a combination of static load, represented by a constant admittance and an equivalent induction motor.

When the structure of the load model is assumed known, estimation of its parameters is an important and difficult task to complete the load model. The main goal of this paper is to illustrate the results of load parameter identification using field data recorded from passive experimental tests. In this context, this paper will be organized as follows: next section presents the load model parameters estimation strategy; section 3 describes load model structure adopted; section 4 presents a case study, the last section contains the conclusions.

2. LOAD MODEL PARAMETERS ESTIMATION STRATEGY

There exist two approaches to estimate the load model parameters: the component-based method and the measurement-based method. Both have advantages and disadvantages. The component-based method [6], estimates the load parameters from the information on dynamic behavior of each individual component. This information is collected from the survey on the load components. However, such survey for large system loads is a very difficult task and data are often inaccurate. The measurement-based methods used on larger scale, [4], [7], [8], estimate load parameters from the records of the dynamic behavior in the field tests. These tests can be both active and passive. The active tests assume that the perturbations, which determine dynamic load behavior, are made by system operators. The most common possibilities consist of transformers tap changing, large loads, generators or transformers connecting or disconnecting, compensating capacitors switching ON or OFF, etc. Because the active tests can disturb normal operation of the system and the voltage excursions that can result are very small, about 10%, this method is not very efficient, and is not widely accepted [8].

The passive tests consist of the load continuous monitoring and when transients occurred, the data about load behavior is retained and stored by monitoring devices. However the duration for data acquisition, in this case, is much more longer, using passive experimental tests for load model identification is more advantageous. In addition, the proliferation of equipment for real-time monitoring voltage in electrical distribution substations makes this method to become more accessible.

From this point of view, the authors of this paper approached the problem of system load identification by passive field measurements. For this aim has been used voltage, current and power records on several electric lines in HV/MV substations, which were operating in radial scheme. These records were made by protective devices or digital perturbographs placed on the selected lines in a time frame of some months.

Disturbances recorded by monitoring equipment, for the most part, were generated by short circuits on substations buses or on other lines in the area. Since these faults are mostly unbalanced, voltage dips caused by them are also unbalanced. Therefore the algorithm developed for estimating the load model parameters splits the unbalanced three-phase voltages system, $\underline{U}_A$, $\underline{U}_B$, $\underline{U}_C$, into three three-phase balanced systems, of zero, positive and negative sequences, $\underline{U}_0$, $\underline{U}_+$, $\underline{U}_-$ accordingly to Fortescue theorem [9].

$$\begin{bmatrix} \underline{U}_0 \\ \underline{U}_+ \\ \underline{U}_- \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_A \\ \underline{U}_B \\ \underline{U}_C \end{bmatrix} \qquad (1)$$

where $a = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$

So, the effects of unbalanced voltages changing at load terminals can be computed by superposing of the effects of the three balanced voltage systems. For each component (static and dynamic) of the system load model, its behaviour is simulated on balanced voltage perturbations, their effects are then superposed and finally using Eq.1 inverted it returns to phase quantities.

The load model parameter estimation is treated as an error-minimizing problem, which can be sketched conceptually as is shown in Fig.1.

The quantities *v(t)*, represented by bus voltage recorded at load terminals of the true load is applied also to the load model as inputs. The bigger the voltage variation is, the better load parameters estimation can be made. Generally, voltage dips larger than 0.1. p.u. can be used for conclusive results. These voltage dips, recorded in the field measurements were usually in the range 0.1 to 0.3. p.u.

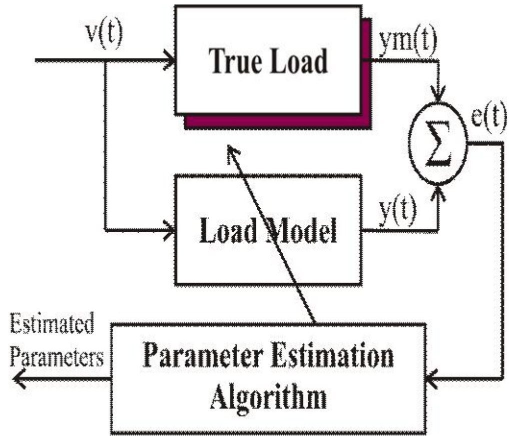

Fig. 1. Measurement based load parameters estimation

During the perturbation, due to the instant voltage disturbance, the true load answers *ym(t),* is assumed to be caused only by voltage variation. However, there exists the possibility that some electric appliances to be switched on or off during this short time period of the recorded voltage dip. Taking into account that voltage dips durations usually may last only tens of milliseconds or even shorter, this small random variation of the load can be neglected, and the load structure can be considered as invariable during recorded perturbation. Exactly the same instant of the recorded voltage is applied to the previously defined load model and its outputs, *y(t)*, are compared with correspondent measured quantities *ym(t).* The difference between *ym(t)* and *y(t)* is fed back to the parameter estimator algorithm so that the parameters of the load model could be adjusted to minimize the expectation of the squared error:

$$J(e^2) = \frac{1}{N}\sum_{i=0}^{N}[ym_i - y_i]^2 \qquad (2)$$

where, ym_i, and y_i, are sampled values of the above defined quantities, and N is the total number of samples, recorded during voltage dip.

The parameter estimation algorithm will modify the model parameters (whose list is given in section 3) so to minimize the above error function, $J(e^2)$ using the well-known method of least squares. To avoid falling into a local minimum is important for initial values of parameters to be chosen closer to the real values. To this aim, the procedure of minimizing the error function is preceded by the adjusting of the initial values of the parameters so that the model response to be as close to that of the true load.

3. LOAD MODEL STRUCTURE ASSUMED

A load model, appropriate to perform analysis of the system, must be a set of mathematical relations between the quantities given by the power system to the load terminals and the quantities by which it responds to its changing. Usually as given quantities, named as inputs, are considered voltage magnitude, noted U, and its frequency, or pulsation, ω. As outputs quantities are

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considered active and reactive powers *P,* and *Q*, flowing in the bus load. These relationships are known as load characteristics, which can be static or dynamic, depending on the system regime described by these.

The static characteristics or the static load model are represented by several algebraic functions, like exponential or polynomial functions, to include the answer of all consumers to the voltage changes at their terminals. This load model is adequate for steady state analysis or for slow changing regimes. For transients analysis the system load model must be considered as a mix of static and dynamic characteristics. In this case it is reasonable to consider the system load composed of a part of static consumers and other part by dynamic consumers. For each part is adopted a distinguished model, and the aggregate model is sum of the two models taking into account their weighting coefficients in total load power. However a universal load model adapting to all situations does not exist. The reason lies in the fact that the load has a random structure with various components and with different characteristics. Under extreme situations some load components may show highly nonlinear characteristics and some motors will drop off.

The reference state active and reactive powers for static and dynamic load components, P_{0_s} and Q_{0_s} and respectively, P_{0_d} and Q_{0_d} will be taken as:

$$\begin{aligned} P_{0\_s} &= r_P \cdot P_0; \quad Q_{0\_s} = r_Q \cdot Q_0 \\ P_{0\_d} &= (1-r_P)\cdot P_0; \quad Q_{0\_d} = (1-r_Q)\cdot Q_0 \end{aligned} \tag{3}$$

where r_P and r_Q are weighting coefficients of the static component in active, respectively reactive, total power, P_0 and Q_0 absorbed by composite load in the reference steady state.

A. Static Load Model

Given that the static component of system load is represented mainly by furnaces, heaters, static capacitors, electronic equipment, lighting consumers etc., it is represented here as a constant admittance:

$$\underline{Y}_{st} = G_{st} - jB_{st} \tag{4}$$

where:

$$G_{st} = \frac{P_{0\_s}}{U_0^2} \quad \text{and} \quad B_{st} = \frac{Q_{0\_s}}{U_0^2}$$

are the components of the load model admittance; and U_0 is bus voltage, in the load reference state.

Consequently, the static load model, that represents the power relationship to voltage, is as follows:

$$P_{\_s} = G_{st} \cdot U^2 \qquad Q_{\_s} = B_{st} \cdot U^2 \tag{5}$$

Some individual static consumers like discharge lighting, exhibit significant discontinuities to voltage excursions under a given threshold. This aspect is considered in static load model, by introducing two admittances, one for continuous, and other for discontinuous component of the static part load. The first one remains connected all the time and the second one will be disconnected if the terminal voltage falls below a certain threshold. Typically this threshold is 80% of rated voltage [1].

B. Dynamic Load Model

Because the dynamic component of the system load is represented by consumers with mechanical and magnetic inertia, such as electric machines, the dynamic load model should express the active and reactive powers at any instant of time as function of the voltage magnitude and its frequency at past instants of time. So it is necessary to use differential equations systems for representing the dynamic part of the load model. So the load model of its dynamic part can be represented either as a black box or as model with clear physical interpretation. The last possibility is widely accepted by system operators.

Given that dynamic component of the composite load is predominantly made up of electric induction motors it is reasonable that it be represented by an equivalent induction motor. Several levels of detail, based on its equivalent circuit can be considered: a dynamic model including the mechanical dynamics but not the flux dynamics; addition of the rotor flux dynamics; and the last model with addition of the stator flux dynamics. Taking into account that the load model which will be identified is intended mainly to be a tool for system stability analysis, the authors considered to be suitable that a dynamic model should include both the mechanical dynamics and the rotor flux dynamics, i.e. a third-order induction motor model. Consequently, the equivalent circuit of the load model as a combination of static and dynamic part can be represented as in Fig. 2.

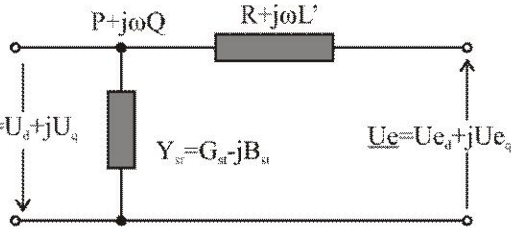

Fig. 2. Equivalent circuit of the load

The input-state-output general form for induction motor model contains a set of differential equations for state variables, denoted by vector $\underline{x}$, and algebraic equations for output quantities, denoted by $\underline{y}$.

$$\begin{aligned} \frac{d\underline{x}}{dt} &= f_x\left(\underline{u}, \underline{x}, \underline{p}\right) \\ \underline{y} &= f_y\left(\underline{u}, \underline{x}, \underline{p}\right) \end{aligned} \tag{6}$$

where electrical quantities and parameters vectors involved, are the following:

$$\underline{x} = \begin{bmatrix} U_{ed} & U_{eq} & s \end{bmatrix}^t$$
$$\underline{u} = \begin{bmatrix} U & \omega \end{bmatrix}^t$$
$$\underline{y} = \begin{bmatrix} P & Q \end{bmatrix}^t$$
$$\underline{p} = \begin{bmatrix} L_s & R & L_s & L' & T'_{d0} & T & K_m & \beta \end{bmatrix}^t$$

where the exponent ^{t} stands for transposed vector.

The equations set (6) makes the link between values offered by the power system, vector $\underline{u}$, the magnitude and speed (frequency) of the terminal voltage (U and ω), to the load terminals, and the characteristic values of the load, by which it responds to system quantities changes. It was considered in this case, the components P, Q of the absorbed powers. As state values, $\underline{x}$ vector, was admitted d-axis and q- axis transient EMF, denoted U_{ed} and respectively, U_{eq}, and rotor slip, s. The vector $\underline{p}$ is the parameter vector, used for dynamic part of the load model developed. The meanings of its components are given in the appendix.

With the above defined vectors, the dynamic part of load model, of the general form (6), can be described by the following set of equations, developed in [10]:

$$
\begin{aligned}
T_{d0}^{'} \cdot \frac{dU_{eq}}{dt} &= -U_{eq} + \left(L_s - L^{'}\right)\omega \cdot I_d - s\omega T_{d0}^{'} U_{ed} \\
T_{d0}^{'} \cdot \frac{dU_{ed}}{dt} &= -U_{ed} - \left(L_s - L^{'}\right)\omega \cdot I_q + s\omega T_{d0}^{'} U_{eq} \\
T \cdot \frac{ds}{dt} &= K_m \left[\omega(1-s)\right]^{\beta+1} - \left(U_{ed} \cdot I_d + U_{eq} \cdot I_q\right)
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
P &= U_d \cdot I_d + U_q \cdot I_q \\
Q &= U_q \cdot I_d - U_d \cdot I_q
\end{aligned}
\tag{8}
$$

where:

$$
\begin{aligned}
&U_d = U \cdot \cos\delta \qquad \mathrm{U}_q = U \cdot \sin\delta \\
&I_d = \left(U_d - U_{ed}\right) \cdot G + \left(U_q - U_{eq}\right) \cdot B \\
&I_q = -\left(U_d - U_{ed}\right) \cdot B + \left(U_q - U_{eq}\right) \cdot G \\
&G = \frac{R}{R^2 + \left(\omega L^{'}\right)^2} \qquad B = \frac{\omega L^{'}}{R^2 + \left(\omega L^{'}\right)^2}
\end{aligned}
$$

The angle δ of the phasor $\underline{U}$ is considered as reported to same angle reference axis, same for both positive and negative voltage sequences. Usually it can be considered on phase A of the three-phase voltage system at load terminals. The first two equations in (6) describe flux decay dynamics, while the third equation is the inertia dynamics of an equivalent induction motor. In this equation, the mechanical torque of the driven mechanism is considered as rotor speed ω'=ω (1–s) dependence:

$$C_m = K_m \ \omega \ (1-s)^{\beta} \tag{9}$$

where the exponent β can vary usually in the range 1 to 2.

The equations (7), determine the model outputs, represented here by the absorbed active and reactive powers. Although several works [11] use current components as outputs, we consider that engineers are more familiar with powers than currents.

The above induction motor model describes its behavior on positive sequence of terminal voltage. If we consider negative voltage sequence the speed of magnetic stator field is $\omega\_ = -\omega$. Consequently the rotor slip $s\_$ to negative sequence will become: $s\_=2-s$. So the mathematical load model described by equations (7) and (8), can be used also for negative voltage sequence by replacing s with $s\_$ in all above equations.

4. STUDY CASE

The proposed algorithm was implemented into application software, and it was used for parameters identification, of some system loads from power system. In this paper, it is presented the identification of the load model for a 110 kV line, from the Sacalaz substation. The monitoring device was connected at the terminals of the 110kV line Sacalaz-Carpinis, and the triggering was set to 0.9 of phase voltage. All data recorded during the 2009 year, were saved in a standard format and were used for load identification. The usage of the software developed is presented below.

At the beginning, it is necessary to upload a file that contains the discrete values of voltages and the currents recorded during the voltage sag. By using the specific techniques, the RMS values for voltages and currents are determined for each moment of time and also the active and reactive powers are computed in the same way. With these computed values the base power and the nominal voltage are selected and on their basis a common set of parameters is chosen.

After that, two charts are drawing, one for the active power and one for the reactive power, each chart contains two curves, one for the real data, red and thick trace and one for the algorithm output, blue and thin trace (Fig.3). Before running the estimation algorithm, a manual adjustment of parameters was made to avoid falling into a local minimum.

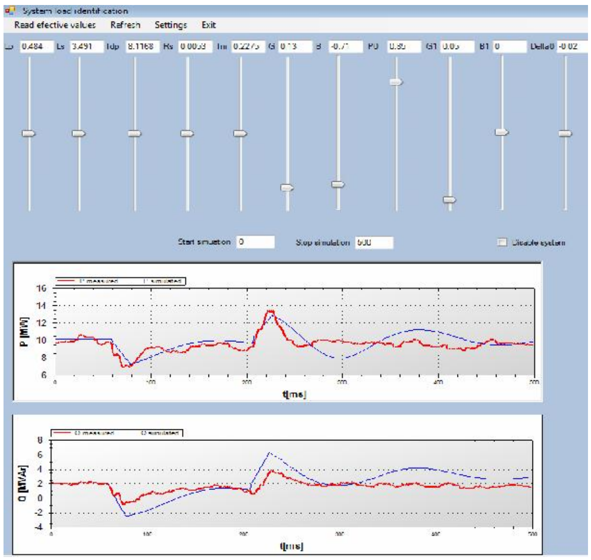

Fig. 3. Initial adjustment of the parameters.

After this initial parameter adjustment, the simulated outputs and the true load became more closer and the success of the estimation algorithm is assured. Starting of the estimation algorithm is made by a software menu option.

Finally, the results obtained from the estimation process for the case of voltage dip represented in Fig.4, are presented graphically in Fig.5 for active power and in Fig.6 for reactive power. Even if the overlapping is not perfect, for the minimum and the maximum points it was obtained the same values, both for the active power red line, and reactive power, blue line.

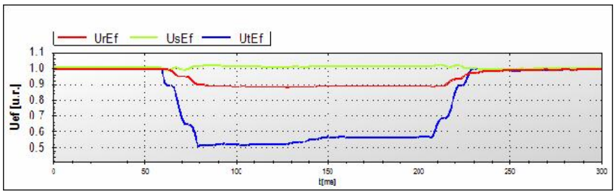

Fig. 4. Phase voltages during voltage dip.

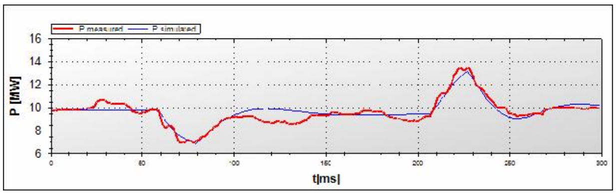

Fig. 5. Active powers after estimation.

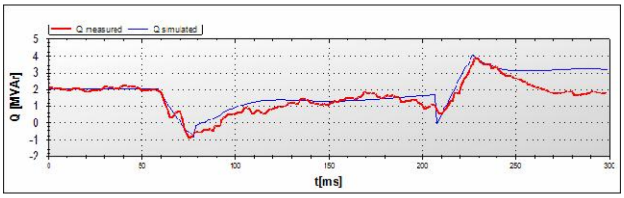

Fig. 6. Reactive powers after estimation.

The estimated parameters for the load can be seen in Table 1 (row 1) for dynamic component and Table 2 (row 1) for static component.

For validating the results, a new file with records was uploaded. The phase voltages for this case are shown in Fig.7. For the new case, the base power remained the same and the power of the load was reduced. In this situation the results obtained with the parameters estimated in first case are presented in Fig.8 for the active power and in Fig.9 for the reactive power. It must be specified that only the susceptance of static component was modified, because the compensation of reactive power is made with capacitor banks.

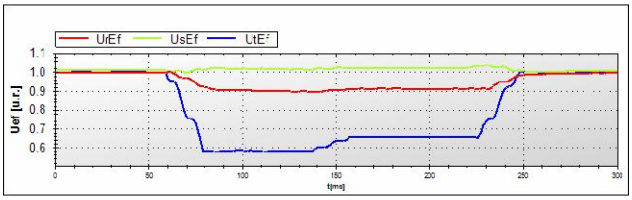

Fig. 7. Phase voltages during voltage dip for new case

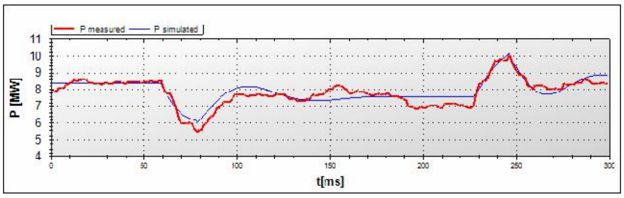

Fig. 8. Active powers for new case

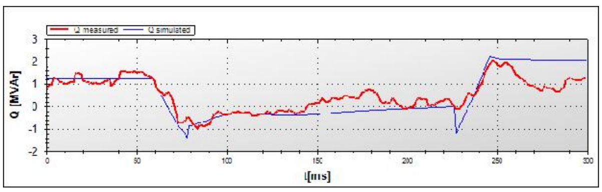

Fig. 9. Reactive powers for new case.

By looking on Fig.8 and Fig.9 it can be noticed that the overlapping is not as good as in Fig.5 and Fig.6 and that the minimum and maximum values present some differences between the real data and the algorithm output. In this situation the estimation algorithm was run again. The results obtained after estimation are presented in Table 1 (row 3) for dynamic component and Table 2 (row 3) for static component.

The same procedure was applied for all the cases recorded in similar conditions (e.g. summer, working day, night,…). The results obtained are showed in Table 1 and 2.

In Table 3 it can be seen the base voltage (U_b) and base power (S_b) chosen for the system load. With P_0 was noted the ante perturbation power of the system load. Finally, in Table 3 are presented the mean square errors for active power (*eP*) and for reactive power (*eQ*), given by relations of type (2), computed as percent from field measured ante-perturbation active power, respectively reactive power.

Table 1. Estimated parameters for dynamic component of system load.

Date	Ls [pu]	L' [pu]	R [pu]	T [s]	T'_{d0} [s]	β
08/07/09,01:15	3.024	0.456	0.141	6.278	0.027	2
08/07/09,02:42	3.352	0.449	0.126	6.847	0.025	2
08/10/09,03:54	2.967	0.472	0.161	5.646	0.026	2
08/13/09,02:51	3.192	0.469	0.152	6.278	0.028	2

Table 2. Estimated parameters for static component of system load.

Date	G [pu]	B [pu]	G1 [pu]
08/07/09,01:15	0.07	-0.44	0.10
08/07/09,02:42	0.07	-0.40	0.10
08/10/09,03:54	0.04	-0.42	0.12
08/13/09,02:51	0.08	-0.47	0.08

Table 3. Base values and mean square errors.

Date	Ub [kV]	Sb MVA	P0 [pu]	eP [%]	eQ [%]
08/07/09,01:15	110	10	0.80	0.2749	1.6883
08/07/09,02:42	110	10	0.80	0.3084	1.8268
08/10/09,03:54	110	10	0.65	0.2410	3.1012
08/13/09,02:51	110	10	0.77	0.2801	1.2808

The same procedure was applied for all the cases recorded in the database. The results showed a variation of parameters in range of ±15% for all the records obtained in similar conditions (e.g. same season, working day/weekend, time frame,…). The values of the resistance *R*, of the stator circuit of the equivalent induction motor, in table 1, had resulted larger as it is usually, because it includes also the distribution line resistance. Differences between field measured active powers and that resulted by simulation, expressed by mean square errors, reported to its ante-perturbation value, *eP%,* have quite reasonable values. But mean square errors, *eQ%*, for reactive powers have larger values because of the nonlinear characteristics of many load components, which can't be included in the load model.

CONCLUSION

Power system analysis and control request an accurate load models to be credible. But load modeling is a very difficult problem due the random nature of the load. This paper has presented a measurement-based composite load model. The assumed structure of the load model is a combination of an induction motor, for the dynamic part of the load and a constant admittance, for its static part.

For model parameter estimation using field-recorded data, has been developed an application software that could lead to a good fitting accurateness. Taking into account that most system faults are unbalanced, the estimation algorithm considers also voltage system at load terminals as unbalanced.

The study cases presented in section 4 prove to be efficient and accurate both the load model assumed and the estimation method used. The efficiency of the computational algorithm by processing recorded data in a high/medium voltage substation was also demonstrated, on some distribution radial lines, during several months in 2009.

However the estimated load model parameters using a limited data sets cannot be considered as generally acceptable. As many recorded data are processed a better estimation is made. Because of changing structure of the true load, estimated parameter sets could be acceptable only for some circumstances. Consequently it's necessary to identify the load model for different situations, as working/nonworking day, season, day and night, etc. In this context a future approach including also statistical methods are to be considered.

The work reported in this paper is just an initial step toward a better understanding the load and the modern possibilities for its model identification.

APPENDIX

List of the symbols of equivalent induction motor parameters:

L_S	Synchronous inductance, (p.u.);
L'	Transient inductance, (p.u.);
R	Equivalent resistance of stator circuit, (p.u.);
T	Motor-load equivalent inertia constant, (sec.);
T'_{d0}	d-axis open circuit time constant, (sec);
K_m, β	Parameters of the mechanical load torque

List of the symbols of equivalent static component parameters:

G	Conductance (p.u.);
B	Susceptance (p.u.);
$G1$	Discontinuous conductance (p.u.).

Other symbols used:

d, q	rectangular axes, rotating with synchronous speed;
δ	angle of the terminal voltage in d-q axis system;
U_d, U_q	d-axis and q-axis bus voltage;
I_d, I_q	d-axis and q-axis stator currents;
ω, ω'	synchronous and rotor speeds, in rad/sec. ;
s	rotor slip of the equivalent induction motor.

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