Technique for Field Data Based Identification of Static Polynomial Load Model

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***Abstract*— the aim of the research is to develop and test technique for obtaining load static characteristics of large industrial enterprise. The research is initiated because the available data about Russian power system load have become outdated due to the change of power system structure, load content and behavior. At the same time the existing methods do not properly solve the problem of ill-conditioned data which is essential for such stochastic system as electrical load. The solution of this problem can be provided only on the basis of multiple experiments accounting different operating conditions of power system. The results of the first stage of such experimental work scheduled for the next several years by Russian System Operator is presented in the paper. To collect the data required for developing and testing of new multistage technique for identification of static polynomial load model, an active experiment was conducted. The proposed technique combines the successive approximation method and least-square method for filtering ill-conditioned data and estimation of polynomial model parameters. The obtained results confirm the efficiency of the proposed technique.**

Keywords*— *load static characteristic; voltage; active power; reactive power; power system; active experiment.

I. INTRODUCTION

One of the main tasks that are solved for energy market operation is evaluation of transmission capacity limits. An accurate solution of this task is extremely important since raw estimations may lead to overstanding of operating margins and as a result to undershooting of power system efficiency improvement capabilities.

It is a well-known fact that accuracy of transmission capacity limits estimation is significantly dependent on the choice of electrical load simulation approach. Simulation of electrical load is complicated when it concerns a large power system state estimation tasks because each power system node consists of a large number of power consumers with different capacity, parameters, load factor and operating conditions.

The load simulation task became of great importance after several large outages over the world, when the lack of accurate information about characteristics of electrical load led to loss of power system stability, complication of load restoration in post fault conditions and significant damage [1-3].

The increasing interest of Russian electrical utilities to the improvement of electrical load model performance is connected with aging of data about load static characteristics that had been estimated last time more than twenty years ago. The precise attention to the static characteristic can be explained by the fact that they are used in power system software intended for solution of dispatching control and wholesale electricity market tasks [4].

II. PERFORMANCE OF EXPERIMENT

This paper is based on results of active experiment that was conducted for consumers of 35/6 kV substation of a cable factory to identify the parameters of voltage dependent static characteristics of a load connected to 6 kV busbar. Experiment consisted of changing the position of on-load tap changer of 10 MVA power transformer supplying the load.

The experiment was conducted under the following conditions:

- The frequency was stabilized and approximately equal to the rated value of 50 Hz.
- The available range of voltage change during experiment was not less than 15 % of the rated voltage value U_{rated} (the maximum voltage value is limited by power equipment operating limits and the minimum value was limited by the load stability margin).
- The measurements were done with multichannel portable power analyzer AR5 CIRCUTOR which allowed recordkeeping and transfer the data to the personal computer. The analyzer was connected to the voltage and current measurement transformers with accuracy classes of 0.5 and 0.2S respectively.

Three phase voltage U_i, active P_i and reactive Q_i power values were obtained and stored in arrays for processing.

III. TECHNIQUE OF DATA PROCESSING

Voltage dependent static load characteristics are the dependencies of load active or reactive power on applied voltage in steady state conditions. These characteristics are most commonly performed as polynomial functions:

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$$P = P_{BASE} \cdot \left(a_0 + a_1 \frac{V}{V_{BASE}} + a_2 \left(\frac{V}{V_{BASE}} \right)^2 \right); \quad (1)$$

$$Q = Q_{BASE} \cdot \left(b_0 + b_1 \frac{V}{V_{BASE}} + b_2 \left(\frac{V}{V_{BASE}} \right)^2 \right). \quad (2)$$

where V_{BASE}, P_{BASE}, Q_{BASE} – base values of voltage, active and reactive power corresponding to the base voltage;

a_0, a_1, a_2, b_0, b_1, b_2 – polynomial coefficients.

The experimental data consist of regular and stochastic components of consumed power. The regular component contains information about consumption level according to the load profile and stochastic component includes random change of load and measurement errors that are considered as a noise.

One of the most popular methods used to estimate polynomial coefficients in the presence of noise is least squares approximation.

The values of V_i, P_i, Q_i, obtained for the time instant t_i are called further in the text as a point i.

The voltage corresponding to the neutral position of the tap changer is accepted as a base V_{BASE}. The value of the base voltage is a constant. The values of the voltage V_i should be put in p.u. according to the formula:

$$V_{*i} = \frac{V_i}{V_{BASE}}. \quad (3)$$

The data that correspond to the instants just before and right after the voltage change should be extracted from the arrays to exclude most of the stochastic component. It can be done by selecting two closest points at the time scale before and after power transformer tap changing.

Each tap of a power transformer allows changing the voltage by 1% or more thus the following conditions can be applied to indicate two points corresponding to tap changing:

$$| V_{*i+1} - V_{*i} | \cdot 100\% > 1\%. \quad (4)$$

The selection of pairs of points gives $M+1$ segments of a load characteristic. If the beginning of each segment has index $2 \cdot j$ and end of a segment is $2 \cdot j+1$ then an array of all the first points of all segments can be designated as $V_{*2 \cdot j}$, $P_{2 \cdot j}$, $Q_{2 \cdot j}$, and array of second points of all segments is $V_{*2 \cdot j+1}$, $P_{2 \cdot j+1}$, $Q_{2 \cdot j+1}$.

The proposed technique is based on the assumption that P_{BASEj} and Q_{BASEj} are constant for the beginning and end points of all segments. Therefore the points corresponding to the change of base power values should be excluded.

To do this, the power regulation coefficients of load KP_j and KQ_j are evaluated for the pairs of points by the formulas:

$$KP_j = \frac{P_{2 \cdot j+1} - P_{2 \cdot j}}{V_{*2 \cdot j+1} - V_{*2 \cdot j}} \cdot \frac{V_{*2 \cdot j+1} + V_{*2 \cdot j}}{P_{2 \cdot j+1} + P_{2 \cdot j}}; \quad (5)$$

$$KQ_j = \frac{Q_{2 \cdot j+1} - Q_{2 \cdot j}}{V_{*2 \cdot j+1} - V_{*2 \cdot j}} \cdot \frac{V_{*2 \cdot j+1} + V_{*2 \cdot j}}{Q_{2 \cdot j+1} + Q_{2 \cdot j}}. \quad (6)$$

If base power is different for the beginning and end points of the same segment (between instants $t_{2 \cdot j}$ and $t_{2 \cdot j+1}$) then estimated power regulation coefficients will differ from the values estimated when P_{BASEj} and Q_{BASEj} are constant.

The results obtained from the active experiment showed that the data eliminated from the arrays of active and reactive power do not correspond to the same instants of time. This is accounted by including independent procedures for elimination of stochastic active and reactive power data and adding corresponding indexes P and Q to the equations.

The method of successive approximations is chosen as the basis for identification of load static characteristics $P(V)$ and $Q(V)$. This is step by step method allowing finding the sequence of improving approximate solutions.

The first approximation includes the calculation of base power values which are used for estimation of p.u. values of active and reactive power and polynomial coefficients.

To find the base power values, the bisecting points of segments should be calculated as:

$$V_{*(bisjP)} = \frac{V_{*(2 \cdot jP+1)} + V_{*(2 \cdot jP)}}{2}; \; P_{(bisjP)} = \frac{P_{(2 \cdot jP+1)} + P_{(2 \cdot jP)}}{2}; \quad (7)$$

$$V_{*(bisjQ)} = \frac{V_{*(2 \cdot jQ+1)} + V_{*(2 \cdot jQ)}}{2}; Q_{(bisjQ)} = \frac{Q_{(2 \cdot jQ+1)} + Q_{(2 \cdot jQ)}}{2}. \quad (8)$$

The base power of the first segment can be found if we assume that the average power value for this segment is equal to 1 p.u. This assumption is true if active experiment starts when the tap changer of a power transformer is in the neutral position and the voltage is close to its base value. In this case

$$P_{BASE(0)} = P_{bis(0)}; \; Q_{BASE(0)} = Q_{bis(0)}. \quad (9)$$

The base power values of the other segments can be obtained under conditions in which active and reactive power values in p. u. remain the same.

If the base power of the j segment is known then the base power of $j+1$ segment can be evaluated as:

$$P_{BASE(j_P+1)} = \frac{P_{2 \cdot j_P+2} \cdot P_{BASE(j_P)}}{P_{2 \cdot j_P+1}}; Q_{BASE(j_Q+1)} = \frac{Q_{2 \cdot j_Q+2} \cdot Q_{BASE(j_Q)}}{Q_{2 \cdot j_Q+1}}. \quad (10)$$

The method of least squares is used then to derive a system of equations like:

$$\begin{pmatrix} P_{*0} \\ P_{*1} \\ \dots \\ P_{*M_P+1} \end{pmatrix} = \begin{pmatrix} 1 & V_{*0} & V_{*0}^2 \\ 1 & V_{*1} & V_{*1}^2 \\ . & . & . \\ 1 & V_{*M_P+1} & V_{*M_P+1}^2 \end{pmatrix} \cdot \begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix}. \quad (11)$$

To solve the system of equations (11), the following designations should be introduced:

$$x=\begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix};\ b=\begin{pmatrix} P_{*0} \\ P_{*1} \\ \dots \\ P_{*M_P+1} \end{pmatrix};\ A=\begin{pmatrix} 1 & V_{*0} & V_{*0}^2 \\ 1 & V_{*1} & V_{*1}^2 \\ . & . & . \\ 1 & V_{*M_P+1} & V_{*M_P+1}^2 \end{pmatrix}. \quad (12)$$

If the least sum of squares criterion is applied to both parts of the system of equations, i.e.

$$\left(Ax-b\right)^T\cdot\left(Ax-b\right)\rightarrow \min, \quad (13)$$

the following solution would be obtained

$$A^T Ax = A^T b \quad \Rightarrow \quad x=\left(A^T A\right)^{-1}\cdot A^T b. \quad (14)$$

where A^T – transpose of matrix.

The values of obtained polynomial coefficients a_0, a_1, a_2 and b_0, b_1, b_2 are the first approximation.

If it is considered that the base power is constant for whole segment j, then the method of successive approximations can be used to calculate a base power for each segment:

$$P_{BASE(j_P)}=\frac{P_{bis\,j_P}}{a_0+a_1\cdot V_{*bis\,j_P}+a_2\cdot V_{*bis\,j_P}^2}; \quad (15)$$

$$Q_{BASE(j_Q)}=\frac{Q_{bis\,j_Q}}{b_0+b_1\cdot U_{*bis\,j_Q}+b_2\cdot U_{*bis\,j_Q}^2}. \quad (16)$$

Then the algorithm of polynomial coefficients estimation should be repeated again step by step from (11) to (14) to obtain adjusted values of a_0, a_1, a_2 and b_0, b_1, b_2.

It should be noted that the approximation method does not consider the conditions

$$a_0+a_1+a_2=1;\ \ b_0+b_1+b_2=1. \quad (17)$$

Therefore each approximation can lead to moving load static characteristics away from the point with coordinates (1;1). To exclude this, the obtained polynomial coefficients should be multiplied each time by

$\frac{1}{a_0+a_1+a_2}$ and $\frac{1}{b_0+b_1+b_2}$ for active and reactive power respectively.

It is suggested to use the mean square deviation values for estimation of the accuracy of all selected p. u. values of power:

$$\sigma_P=\sqrt{\frac{1}{2\cdot M_P+2}\sum_{i_P=0}^{2\cdot Mp+1}\left[P_{*i_P}-\left(a_0+a_1\cdot V_{*i_P}+a_2\cdot V_{*i_P}^2\right)\right]^2} \quad (18)$$

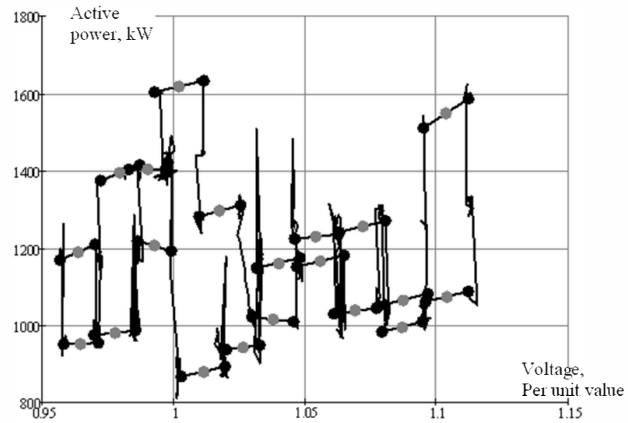
$$\sigma_Q=\sqrt{\frac{1}{2\cdot M_Q+2}\sum_{i_Q=0}^{2\cdot M_Q+1}\left[Q_{*i_Q}-\left(b_0+b_1\cdot V_{*i_Q}+b_2\cdot V_{*i_Q}^2\right)\right]^2} \quad (19)$$

The approximation procedures should be repeated while the values of mean square deviations get smaller with each following approximation.

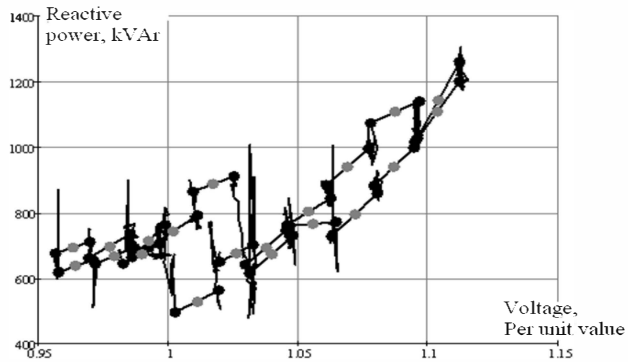
IV. Test Results of the Technique

The technique for identification of static polynomial load model introduced above was tested on data containing N+1=489 sets of voltage, active and reactive power values obtained from active experiment described in chapter I.

The closest points selected independently from active and reactive power data sets according to (4) are given in Fig. 1.



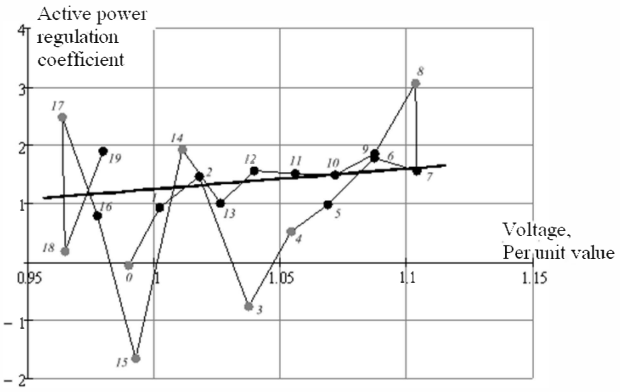
a)



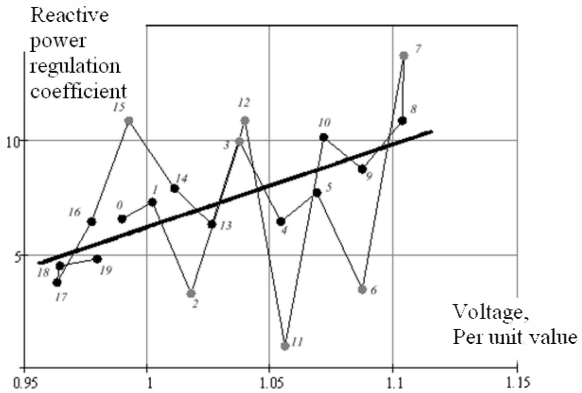
b)

Fig. 1. The closest points near the instants of tap changing for active (a) and reactive (b) power data sets

The power regulation coefficients KPj and KQj were estimated by (5) and (6) to eliminate the pairs of points with different base power values. The results are given in Fig. 2.



a)

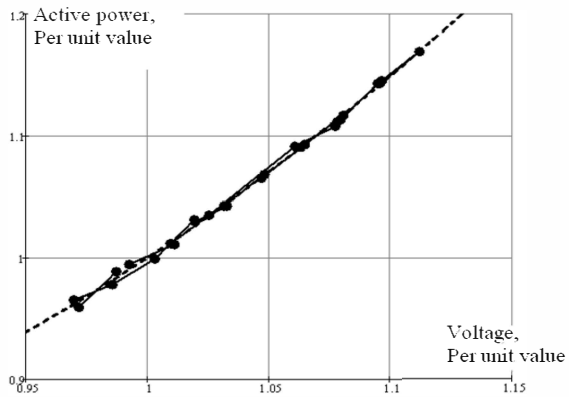


b)

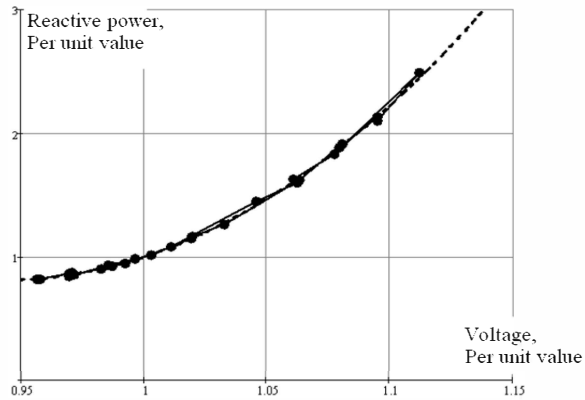
Fig. 2. The power regulation coefficients *KPj* (a) and *KQj* (b).

The sequence numbers of the points eliminated from the arrays of active and reactive power are different. The eliminated points for active power are 15, 3, 0, 18, 8, 4, 17, 14 and for reactive power are 11, 15, 6, 7, 2, 12, 3.

Fig. 3 illustrates the final results of approximation for active and reactive power. The accuracy of results was controlled by formulas (18) and (19).



a)



b)

Fig. 3. The results of approximation for active (a) and reactive (b) power

Table I contains the polynomial coefficients of voltage dependent load static characteristics and mean square deviations obtained for the first and last approximation steps.

TABLE I. POLYNOMIAL COEFFICIENTS AND MEAN SQUARE DEVIATIONS

Approximation step	a_0	a_1	a_2	σ_P
0	1.387	-1.794	1.392	0.014
115	1.481	-2.277	1.796	0.003
	b_0	b_1	b_2	σ_Q
0	-13.103	22.668	-8.628	0.138
66	52.048	-108.651	57.599	0.016

V. DISCUSSION AND CONCLUSION

1. The obtained results confirm the efficiency of the proposed technique.

2. The voltage deviations provided during the active experiment were between $(0.97 \div 1.14)\cdot V_{BASE}$. The static characteristics of active and reactive power obtained within this voltage range have small differences, see Fig.3. However the values of polynomial coefficients change significantly, see table I.

3. Depending on the set of the data used for calculation, the power regulation coefficients are between 0.878 and 1.465 for active power and between 5.419 and 6.835 for reactive power, which allow considering them as stable. The regulation coefficients obtained at the final approximation step are K_{Pj} = 1.224 for active and K_{Qj} = 6.547 for reactive power which correspond to the values usual for 6-110 kV networks.

4. The results of active power data processing show that the bending of active power characteristic is so small that it can be convex or concave depending on the data selected for identification. The bending of reactive power characteristic is evident thus it can be accurately approximated with the second order polynomial function and its polynomial coefficients can be accurately defined.

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