DETERMINATION OF DYNAMIC LOAD MODEL PARAMETERS

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INTRODUCTION

Calculation results of voltage and angular stability depend very much on selection of the load model and its parameters, Kundur (1) and Milanovic and Hiskens (2). The knowledge of exact load model parameters, which properly depict load behavior during electric power system disturbances, enables possibility for proper power system planning, exact prediction of prospective scenarios, as well as assumption of corresponding actions for the prevention of unwished consequences.

Many researches have investigated load modeling, suggested own models and determined concrete parameters by the experiments. Which one of numerous developed models will be used depends on load composition and the purpose of the corresponding model. The survey of static and dynamic load models and their parameters that are developed by 1995 are presented in IEEE Task Force on Load Representation for Dynamic Performance (3). Standard models for different purposes and different load compositions are recommended in IEEE Task Force on Load Representation for Dynamic Performance (4) and (5).

As rule, load model parameters of certain low voltage load components are reported in the literature. Load characteristics on higher voltage levels depend on load composition at lower voltages. If the composition and certain load component parameters are known, equivalent load parameters can be determined by aggregation method, Ribeiro and Lange (6). However, exact load composition at medium and high voltage is very difficult to evaluate, thereby the results obtained by the aggregation should be used with reserve. On distribution voltage levels, this approach may yield improbable coefficient values, Milanovic (7). Therefore, simulation results may be unreliable, and the best is to determine load model parameters by experiments for each concrete case. Dynamic load model parameters obtained on the basis of measurements are presented in Karlsson and Hill (8), Navarro, Samuelsson and Lindah (9).

Experimentally determined data at one location, for particular load composition, can not be uncritically

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used under other conditions and in other electrical power systems. Literature load model data may be used only for preliminary calculations and comparative analyses. Also, it should be emphasized that load composition at a node changes during the year, particularly when electrical power is used for heating, as in many parts of electrical power system of Public Enterprise „Electric power industry of Serbia". Resistive load device participation in the total load depends on the tariffs, so daily load composition variations are possible. Owing to all mentioned facts, the authors of this paper are performed series of activities and experiments for dynamic load model parameter determination on distribution level (10kV) of Nis electrical power network. Field measurements are performed in three day intervals of three winter days. Thus, pretty large data base for statistical processing and analyses is created.

DYNAMIC LOAD MODEL OF RESIDENTIAL LOAD

The usage of particular dynamic load model depends on the load composition. Thus, in (8) the first order dynamic load model is suggested and it is confirmed to be convenient for modeling of residential load behavior:

$$T_p \frac{dP_r}{dt} + P_r = P_s(V) - P_t(V) = P_0\left(\frac{V}{V_0}\right)^{\alpha_s} - P_0\left(\frac{V}{V_0}\right)^{\alpha_t}, \tag{1}$$

$$P_l = P_r + P_0\left(\frac{V}{V_0}\right)^{\alpha_t}, \tag{2}$$

where P_r - real power recovery, P_0 - initial value of real power before the voltage change, V_0 - initial voltage value, T_p - real power recovery time constant, α_s - steady state real power voltage exponent, α_t - transient real power voltage exponent and P_l - real power consumption. Since $P_s(V)$ and $P_t(V)$ in this model are expressed by exponential functions, the model is called exponential dynamic load model.

According to the equations (1) and (2), real power response to step voltage change is the function

$$P_l(t) = \left(P_0\left(\frac{V}{V_0}\right)^{\alpha_s} - P_0\left(\frac{V}{V_0}\right)^{\alpha_t}\right)\cdot\left(1 - e^{-t/T_p}\right) + P_0\left(\frac{V}{V_0}\right)^{\alpha_t}, \tag{3}$$

while reactive power response, $Q_l(t)$, is the function of the same form with initial value of reactive power Q_0 and different parameters, β_s, β_t and T_q. Thus generic real power response to ideal step voltage change is presented in Fig. 1. Owing to the voltage decrease real power immediately decreases to $P_t(V)$ value, and then recovers to the value $P_s(V)$, the new steady state value that is determined by load parameters.

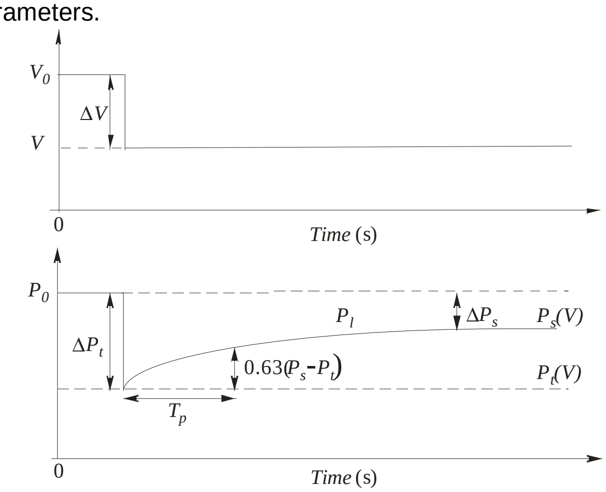

Fig. 1. Generic load response to voltage step

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DETERMINATION OF THE PARAMETERS

General

For parameter determination on the basis of field measurements the abrupt voltage change that cause the load response from Fig. 1 can be induced by different kinds of experiments. One of this experiments consists of manual change of transformer ratio by on-load tap changer. Also, the abrupt voltage change can be caused by switching on/off significant part of the consumption, or more preferably, by switching on/off capacitors banks, if they exist. An interesting procedure for the induction of the abrupt voltage change is realized in (8) since the load of one of two transformers that operate in parallel move to another transformer.

Unknown parameters of exponential dynamic load model of real (α_s, α_t, T_p) and reactive power (β_s, β_t, T_q) can be determined by least square method, Nelles (10). In the case of the identification of real power parameters this method implies the minimization of the function

$$J = \sum_{i=1}^{n} \left(P_m(t_i) - P_l(t_i)\right)^2 , \qquad (4)$$

where $P_m(t_i)$ and $P_l(t_i)$ denote measured values of the power and selected model function, respectively.

Remarks about Field Measurements

This work presents the results of load model parameter identification based on field measurements. These measurements were performed on low voltage side of the transformer 110/10kV and at the beginning of one of 10kV feeders during abrupt voltage changes caused by on-load tap changer. Simplified experiment scheme is depicted in Fig 2. Digital acquisition data devices are connected over existing current (CT) and voltage transformers (VT). The devices record rms voltage values $V(t)$, real $P_m(t)$ and reactive power $Q_m(t)$ at each second.

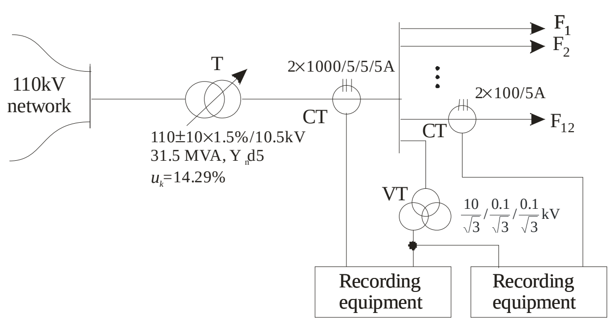

Fig. 2. Simplified experimental scheme

Since the residential load is dominated component of total 110/10kV transformer load (93.25%) and also dominated load component of the feeder (“Nikoletina Bursac”) where the measurements were performed, exponential dynamic load model is selected and real and reactive power responses are fitted by the curves of the form (3).

The experiment on real network substantially differs from the laboratory measurement. Beside equipment risks and unpleasant voltage changes for the consumers, there are parameter identification problems connected with random and regular load changes. In order to obtain dynamic load model parameters more precisely, the measurements should be performed in those day intervals (morning, afternoon and night) when variations of the load are relatively small. According to recorded daily load curve and the experience of distribution company workers in TS "Nis 13” the intervals from 9:30 to 11:15, from 16 to 17:45 and from 20 to 21:45 were selected for the measurements. In these intervals, during 105 minutes, the series from six to eight experiments, of the voltage change within the limits from 0.95 to 1.1p.u. were performed.

Also, it was necessary to determine the time needed for real and reactive power recovery after the voltage change, and the calculation interval that yields the best fitting of power responses. Experiment duration and calculation interval should be determined carefully. On one hand there should be longer interval to have enough data for the identification, and on the other hand for longer intervals unavoidable regular load changes can occur. Therefore, experiment duration was varied from 5 to 20 minutes.

The fitting of real and reactive power responses are performed by the program ORIGIN 7.5 that uses Levenberg-Marquardt algorithm, Gill, Murray and Wright (11). Different intervals (data windows) are used for the fitting - minimum 50 points (50s), maximum so many points (seconds) as one voltage value kept constant, with the step of 50s. Then, the parameters that describe the quality of every fitting are mutually compared. These parameters are:

- $\chi^2 = \frac{1}{N-p}\sum_i \left(P_m(t_i) - P_l(t_i)\right)^2$, where *N* and *p* are total number of experimental points and total number of adjustable parameters, respectively;
- correlation coefficient $R = \sqrt{1 - \frac{\sum_i \left(P_m(t_i) - P_l(t_i)\right)^2}{\sum_i \left(P_m(t_i) - \overline{P_m}\right)}}$ where $\overline{P_m}$ denotes average measured power,
- the errors of parameter determination, $\varepsilon_i = \sqrt{C_{ii} \cdot \chi^2}$, where C_{ii} is the diagonal element of the variance-covariance matrix defined as $C = \left[F' \otimes F\right]^{-1}$ where F is the Jacobian with the elements $F_{ij} = \partial P_l(t_{i,} p_j) / \partial p_j$.

By the analysis of the fitting results of over hundred power responses to abrupt voltage changes some general observations are made:

- fitting within shorter time intervals very often yields smaller values of χ^2 and larger values of R in comparison with the fittings within longer time intervals. It indicates that random load variations become significant after longer time intervals;
- for shorter time intervals the parameters α_t and β_t are determined more precisely - with smaller errors of parameter determination in comparison with these parameters obtained for longer time intervals;
- for longer intervals α_s, β_s, and time constants T_p and T_q are determined with smaller errors than these parameters obtained for shorter time intervals;
- typical errors of parameter determination of α_s, β_s, α_t and β_t are several per mills, while the errors of the determination of time constants are several percents.

The New Criterion for Time Interval Selection

Having in mind all mentioned facts, one new criterion for the selection of time interval that yields the best fitting of the power response have been defined. This criterion consists of several steps:

1. for every time interval (with 50s step) that yield the correlation coefficient larger than 0.7 exponential model parameters and their errors are considered;
2. the errors of parameter determination are expressed in percents of the values of corresponding parameters;
3. since percentile errors of voltage exponents α_s and α_t, as well as percentile errors of β_s and β_t (if reactive power response is considered) are of similar order - several per mills), mean value of α_s and α_t (or β_s and β_t) is find for every time interval;

4. the rank of fitting quality regarding voltage exponent errors is ordered starting with the time interval yielding smallest mean value of α_s and α_t percentile errors (or β_s and β_t percentile errors);
5. the rank of fitting quality regarding time constant errors is ordered starting with the time interval yielding smallest percentile error of time constant T_p (or T_q);
6. the ranks obtained according to step 4 and step 5 should be summed and that yields the final fitting rank. It denotes the best fitting is the one that has the smallest value of final fitting rank;
7. if the final fitting rank is the same for two different time intervals, the interval with lower parameter dependency is chosen indicating the mutual dependency between parameters is lower.

One example of real power response to voltage change is presented in Fig. 3 along with the best fitting for the time interval of 500s according to described new criterion. Maximum deviation of the fitting curve from measured data amounts only 1.01%. Demonstration of the new criterion is presented in Table 1. This table presents data intervals in seconds, corresponding parameters α_s, α_t and T_p obtained by LM algorithm, absolute errors of parameter determination ε_{α_s}, ε_{α_t} and ε_{T_p}, percentile errors of parameter determination $\varepsilon_{\alpha_s\%}$, $\varepsilon_{\alpha_t\%}$ and $\varepsilon_{T_p\%}$, then χ^2 and correlation coefficient R, as well as the rank of fitting according to voltage exponent errors R_1, the rank of fitting according time constant errors R_2 and the final fitting rank R_3. The values from the table show that although fitting curves for relatively short time intervals, 50 and 100s, match the measured values of real power very well and therefore have smallest values of χ^2 and R, they do not correspond the load response from equation (3) and yield enormous errors of the parameters α_s and T_p. Fitting curves for these short periods of time are practically straight lines. This demonstrates the described criteria that treats the percent errors of the parameters is more suitable for the selection of the best fitting than consideration of χ^2 or R. The fitting for 500s time interval is favorable according to the new criteria because R_3 is the smallest. At the same time the values of χ^2 and R are quite good for selected time interval - R amounts 0.9289 and it is highly beyond the selected limit of 0.7 for the correlation coefficient. Also, from Fig. 3 it is obvious that after 500s randomly changes starts to be significant and therefore larger percent errors for the parameters are obtained.

On the basis of all performed experiments and the fittings of power responses it is found that optimal results of real power model for the considered 10kV network are obtained for calculation interval from 500 to 550s. It is somewhat longer that three time constants. Similarly, optimal results of reactive power model are obtained for calculation intervals of about 500s.

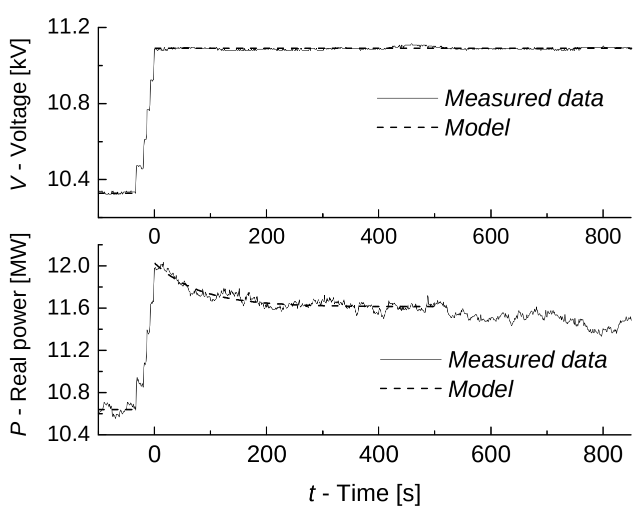

Fig. 3. Measured voltage and real power values along with the fitting curve for time interval of 500s

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TABLE 1 - LOAD MODEL PARAMETERS OBTAINED FOR DIFFERENT TIME INTERVALS, THEIR ABSOLUTE AND PERCENTILE ERRORS, χ^2, CORRELATION COEFFICIENT R AND FITTING RANKS R_1, R_2 AND R_3

Time [s]	α_s	α_t	T_p [s]	ε_{α_s}	ε_{α_t}	ε_{T_p} [s]	$\varepsilon_{\alpha_s}\%$ [%]	$\varepsilon_{\alpha_t}\%$ [%]	$\varepsilon_{T_p}\%$ [%]	χ^2	R	R_1	R_2	R_3
850	0.9901	1.5497	398.66	0.0158	0.0086	27.42	1.5989	0.5556	6.88	0.00318	0.8961	15	12	27
800	1.0532	1.5712	301.84	0.0110	0.0092	18.51	1.0473	0.5836	6.13	0.00308	0.8918	13	11	24
750	1.1378	1.6251	178.53	0.0051	0.0095	7.95	0.4517	0.5840	4.46	0.00237	0.9036	7	4	11
700	1.1552	1.6417	155.72	0.0049	0.0100	7.02	0.4250	0.6109	4.51	0.00237	0.9022	8	6	14
650	1.1654	1.6520	143.42	0.0051	0.0106	6.81	0.4402	0.6428	4.75	0.00245	0.8992	9	9	18
600	1.1949	1.6847	111.65	0.0043	0.0112	5.04	0.3599	0.6666	4.52	0.00223	0.8157	6	7	13
550	1.2243	1.7177	86.866	0.0034	0.0109	3.50	0.2793	0.6328	4.03	0.00167	0.9200	2	2	4
500	1.2330	1.7267	80.93	0.0034	0.0106	3.22	0.2790	0.6168	3.98	0.00149	0.9289	**1**	**1**	**2**
450	1.2339	1.7276	80.32	0.0040	0.0110	3.44	0.3217	0.6350	4.29	0.00154	0.9300	3	3	6
400	1.2441	1.7362	74.56	0.0043	0.0112	3.33	0.3432	0.6439	4.47	0.00147	0.9338	4	5	9
350	1.2587	1.7475	67.24	0.0045	0.0114	3.14	0.3591	0.6535	4.66	0.00137	0.8796	5	8	13
300	1.2452	1.7392	73.24	0.0064	0.0115	3.96	0.5156	0.6618	5.40	0.00142	0.9416	10	10	20
250	1.2252	1.7288	82.11	0.0111	0.0120	5.86	0.9043	0.6970	7.13	0.00155	0.8842	12	13	25
200	1.2903	1.7558	57.98	0.0100	0.0137	4.50	0.7750	0.7780	7.76	0.00147	0.9346	11	14	25
150	1.3237	1.7687	48.05	0.0129	0.0149	4.64	0.9745	0.8419	9.65	0.00138	0.9335	14	15	29
100	0.7070	1.7327	186.40	0.3319	0.0106	75.80	46.937	0.6141	40.7	0.00078	**0.9647**	16	16	32
50	-60.16	1.7242	3184.2	39883	0.0141	114951	-66290	0.8207	3610	**0.00075**	0.8032	17	17	34

Simplified Determination of the Parameters

The method of parameter determination of three parameters at the same time based on curve fitting that uses least square method is used in this paper. However, under the assumption that the voltage change is step, (8), one of the parameters, α_t or β_t can be determined using the voltage and power just before the step-change, and the voltage and power immediately after the step, V_+, and P_+ (Q_+):

$$\alpha_t = \frac{\log \frac{P_+}{P_0}}{\log \frac{V_+}{V_0}}, \; \beta_t = \frac{\log \frac{Q_+}{Q_0}}{\log \frac{V_+}{V_0}}. \qquad (5)$$

Using α_t obtained in this way the equation (3) becomes with two parameters that should be identified, α_s and T_p. Therefore curve fitting becomes simpler and needs less number of iterations. On the other hand the fitting curves have larger χ^2 and smaller correlation coefficients, i. e. the fitting is not so good as the fitting using the curve with three unknown parameters. This fact is confirmed through several tents of fittings.

In Fig. 4 measured data of real power response to the voltage change from 10.750kV to 9.688kV performed in the morning of winter working day and the fitting curves with three a) and two unknown parameters b) are presented. The first nonlinear curve fitting needs 4 iterations and yields α_s=1.51, α_t=1.7540 and T_p=156.17s, and the second one needs 5 iterations and gives α_s=1.5132 and T_p=135.49s with previously specified α_t=1.7812. Besides faster calculation, the quality of the fitting from Fig. 4a) is better because χ^2=0.00411 and R=0.8812, while fitting from the Fig. 4b) has χ^2=0.00423 and R=0.8775. Since, somewhat larger number of iterations for nowadays computing

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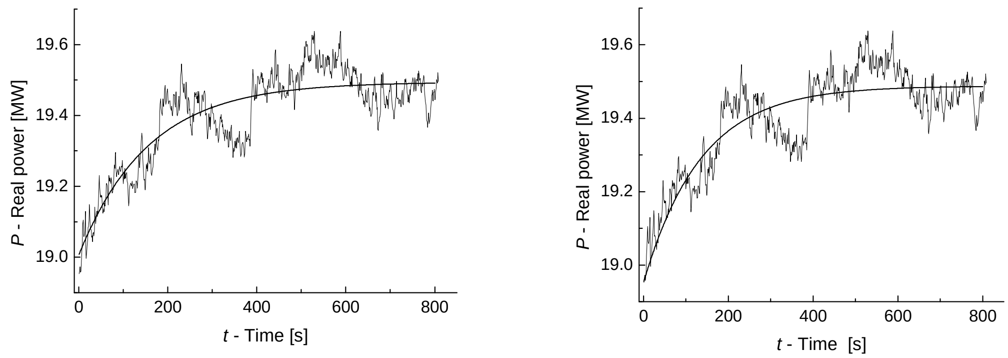
equipment cause small calculation delay (the part of a second) all the results in this paper are obtained by the fitting with the curve of the form of the equation (3) with three unknown parameters.



a) b)

Fig. 4 Real power response to step voltage decrease and the fitting curve with a) three unknown parameters, b) two unknown parameters

THE RESULTS OF PARAMETER DETERMINATION

On the basis of the comparison of the parameters obtained in relatively short period of time when it can be considered the load composition is the same and the load value does not change significantly one general conclusion can be made. Particular values of voltage exponents belong to relatively narrow ranges with maximum deviation from the mean value of several percents, while time constants vary in wider ranges. The obvious differences between the parameters are mostly consequence of random load changes and it will be big risk to make conclusions based on only one experiment.

Thus, during three days of winter forty two experiments of voltage change were performed in different day intervals. According to the adopted criterion that specifies the correlation coefficient should be larger than 0.7 twenty six fittings of total load real power responses and twenty four fittings of total load reactive power responses regarded successful. These numbers of successful experiments are quite large for statistical analyses of the determined parameters. Other experiments were unsuccessful due to load variations.

It was noted that total consumption should be quite large in order to minimize the impact of random load changes. Therefore, low consumption of the selected feeder ($P_{\max} \leq 2.3\text{MW}$ during the experiments) and large random load variations induced the load parameters were hardly identified. Thus, the suggested criterion was corrected and correlation coefficient R>0.5 was selected as the indication the fitting is successful. In that way twenty seven successful experiments for real power were found, and twenty four for reactive power.

The results of voltage exponent determination are given through parameter mean values and their standard deviations in Table 2 for total load of the transformer and the load of considered feeder. The results show that the parameters of feeder load are less reliable and have more than two times larger standard deviations than the parameters of total load. It was expected because of more significant influence of random load changes on feeder load responses. Mean values of the time constants of total load amount T_p =169.27s and T_q =137.55s, while the time constants of feeder load are smaller T_p =124.76s and T_q =86.87s.

The obvious differences in mean parameter values for total load and the load of the feeder indicates the need to consider the load structure and load parameters of the feeders in more details. Namely, although the loads of the transformer and the feeder are predominantly residential there are differences in percentile participation of individual load components. For example, feeder “Nikoletina Bursac” namely supplies suburban residential load (74.52% of the installed power), than residential

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load without central heating (20.32%) and a gas station (5.16%) while 110/10kV transformer supplies residential load without central heating (48.01%), residential load with central heating (14.39%), villages (15.58%), suburban residential load (15.27%), hospitals (5.15%) and commercial load (1.6%).

TABLE 2 - MEAN VALUES AND STANDARD DEVIATIONS OF REAL AND REACTIVE POWER VOLTAGE EXPONENTS FOR TOTAL LOAD AND THE LOAD OF THE FEEDER

Parameter	α_s	α_t	β_s	β_t
Total load	1.3641±0.1457	1.7646±0.0960	3.4371±0.3067	3.7074±0.3006
Load of the feeder	1.0146±0.4517	2.0675±0.3744	2.7184±0.7182	3.6726±0.6933

CONCLUSION

This paper deals with the determination of exponential dynamic load model parameters on the basis of field measurements. The measurements were performed on 10kV voltage side of the transformer that supplies predominantly residential load and at the beginning of one of the feeders. The parameters of exponential dynamic load model were determined by curve fitting of the power responses to voltage step changes in three day intervals when the load and its structure were practically constant. Regarding numerous power responses a new criterion for the selection of time interval (window) that yields the best curve fitting when the parameters are obtained with the smallest errors is introduced.

Presented results of the parameter determination approve the need the parameter should be obtained on the basis of pretty large number of experiments as done in this paper. The results are statistically analyzed and mutually compared. The differences in mean parameter values of total load and the load of the feeder regard the differences in load compositions. The larger values of standard deviations of the parameters of the feeder load are induced by larger influence of random load changes on lower loads. The values presented in this paper can be used for prospective stability calculations and analyses.

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