

## Dynamic Load Modelling of Some Low Voltage Devices

Lidija M. Korunović and Dobrivoje P. Stojanović

**Abstract:** This paper presents the results of dynamic load modelling for some frequently used low voltage devices. The modelling of long-term dynamics is performed on the basis of step changes of supply voltage of the heater, incandescent lamp, mercury lamp, fluorescent lamps, refrigerator, TV set and induction motor. Parameters of dynamic exponential load model of these load devices are identified, analyzed and mutually compared.

**Keywords:** Load modelling, dynamic characteristics, low voltage devices

### 1 Introduction

IT HAS BEEN long recognized that exact load flow calculation is necessary for successful exploitation, control and planning of distribution networks. The accuracy of network condition calculation depends on the precision of input load parameter data. Therefore, numerous researchers have investigated load modelling in the past and proposed various load models. All load models can be divided into two groups, static and dynamic, and their application depends on concrete problem. Static models are mostly used for steady state condition calculations, and dynamic models for studying dynamic phenomena. The majority of static and dynamic load model parameters were determined from field measurements at middle and high voltage levels.

However, load characteristics at higher voltage levels depend on load composition at lower voltages. If the composition and load component parameters are known, equivalent load parameters can be determined by aggregation method [1],

---

Manuscript received on August 23, 2008.

An earlier version of this paper was presented at XLIII International Scientific Conference on Information, Communication and Energy Systems and Technologies, ICEST 2008, June 2008, Niš, Serbia. The authors are with the Faculty of Electronic Engineering, A. Medvedeva 14, 18000 Niš, Republic of Serbia, (e-mail: lidija.korunovic@elfak.ni.ac.rs)

[2]. Generally, static load model parameters of individual low voltage load components are reported in literature. These are parameters of most frequently used exponential and polynomial static load models [3], [4].

Studying of dynamic phenomena, however, require the knowledge of dynamic load model parameters. These parameters are mostly obtained by field measurements, but these measurements are very expensive and also it is not practical to perform them at many buses of the system. Therefore, although measurement based approach is better than composite based approach, since the load composition is very difficult to determine and it changes with time, the latter can be used as alternative way to determine dynamic load model parameters of equivalent load.

Dynamic load model parameters of low voltage devices are very rarely treated in previously published literature [5]. Thus, the parameters of most frequently used exponential dynamic load model at middle and high voltage level, which is also confirmed to be suitable for modelling of middle voltage network load of city of Nis [6], are not identified for low voltage devices by now. Therefore, the aim of this paper is to investigate long-term dynamic performance of some frequently used low voltage devices which are components of previously investigated total load in Nis: to check the adequacy of the model and to identify its parameters. Many laboratory tests on low voltage devices are performed and the most significant ones are presented in the paper.

## 2 Adopted Dynamic Load Model

On the basis of field measurements the mathematical model that describes real and reactive power responses to voltage step is proposed in [7]. This model is called exponential dynamic load model and it is used very often mainly for voltage stability studies. According to the model real power response to the voltage change is given by Eqs. (1) and (2):

$$T_p \frac{dP_r}{dt} + P_r = P_s(U) - P_t(U) = P_0 \left( \frac{U}{U_0} \right)^{\alpha_s} - P_0 \left( \frac{U}{U_0} \right)^{\alpha_t} \quad (1)$$

$$P_l = P_r + P_0 \left( \frac{U}{U_0} \right)^{\alpha_t}, \quad (2)$$

where  $P_r$  - real power recovery,  $P_0$  - initial value of real power before the voltage change,  $U_0$  - initial voltage value,  $T_p$  - real power recovery time constant,  $\alpha_s$  - steady state real power voltage exponent,  $\alpha_t$  - transient real power voltage exponent and  $P_l$  - real power consumption.

Real power response to voltage step change according to Eqs. (1) and (2) is presented in Fig. 1. Following the voltage decrease real power immediately de-

creases to  $P_t(U)$  value, and then recovers exponentially to the value  $P_s(U)$ , i.e., the new steady state value, determined by load parameters.

Reactive power ( $Q$ ) response can be represented using the same form of Eqs. (1) and (2), and is not given here due to the space limitation. In mathematical model for reactive power response the corresponding symbols and coefficients have the following meaning:  $Q_r$  - reactive power recovery,  $Q_0$  - initial value of reactive power before the voltage change,  $T_q$  - reactive power recovery time constant,  $\beta_s$  - steady state reactive power voltage exponent,  $\beta_t$  - transient reactive power voltage exponent and  $Q_l$  - reactive power consumption.

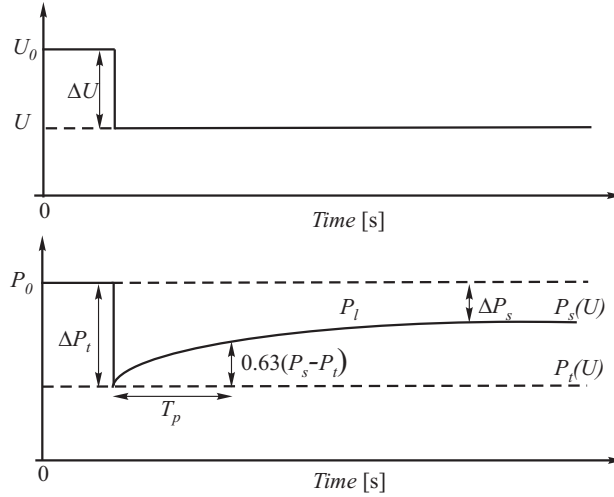


Fig. 1. Load response to voltage step

### 3 Load Model Parameter Identification

Laboratory tests are performed in order to check whether exponential dynamic load model is adequate for modelling of some most frequently used low voltage devices or not, and if yes, to identify the parameters of these devices. The experiments comprehend abrupt change of supply voltage of a device according to the schema from Fig. 2.

During the experiments effective (rms) voltage values  $U(t)$ , real  $P_m(t)$  and reactive power  $Q_m(t)$  are recorded every second (sampling rate 1Hz) by digital data acquisition device, Chauvin Arnoux C.A. 8332. Initial value of device (D) voltage is adjusted by auto-transformer (AT) when switch (SW) was closed. Voltage step-down is simulated by switching off the SW. The value of the voltage change is adjusted by regulating resistor, R. Step-up of the voltage to the initial value is

simulated by switching on the SW.

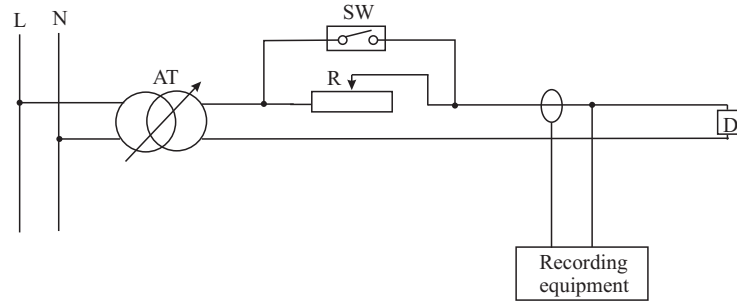


Fig. 2. General schema of laboratory tests

Load model parameters of real power ( $\alpha_s, \alpha_t, T_p$ ) are identified using least square method [6] by minimizing the following objective function

$$J = \sum_{i=1}^N (P_m(t_i) - P_l(t_i))^2, \quad (3)$$

where  $P_m(t_i)$  and  $P_l(t_i)$  denote measured and simulated (based on identified load model parameters) real power response, respectively. Simulated real power response is

$$P_l(t) = \left( P_0 \left( \frac{U}{U_0} \right)^{\alpha_s} - P_0 \left( \frac{U}{U_0} \right)^{\alpha_t} \right) \cdot \left( 1 - e^{-t/T_p} \right) + P_0 \left( \frac{U}{U_0} \right)^{\alpha_t} \quad (4)$$

according to Eqs. (1) and (2). Parameters of reactive power ( $\beta_s, \beta_t, T_q$ ) are obtained by minimizing the objective function similar to Eq. (3) with measured reactive power response,  $Q_m(t_i)$ , and simulated reactive power response

$$Q_l(t) = \left( Q_0 \left( \frac{U}{U_0} \right)^{\beta_s} - Q_0 \left( \frac{U}{U_0} \right)^{\beta_t} \right) \cdot \left( 1 - e^{-t/T_q} \right) + Q_0 \left( \frac{U}{U_0} \right)^{\beta_t}. \quad (5)$$

#### 4 Analysis of the Results

The laboratory experiments are performed on representatives of some frequently used low voltage devices: heater, incandescent lamp, mercury lamp, fluorescent lamps, refrigerator, TV set and induction motor, whose data are given in Appendix. Many measurements are performed to investigate long-term dynamics of these devices, but here are presented the most characteristic results.

On the basis of measurements with power analyzer C.A 8332 that averages the results every second (do not storage the data that correspond to the processes

shorter than 1s), the representative of resistive load devices - the heater, momentary changes its power with voltage change and retains this value during whole experiment (see Fig. 3 obtained when the heater operated with one heating element). Therefore, the power response can be modeled by exponential dynamic load model which voltage exponents are equal,  $\alpha_s \approx \alpha_t = 1.952$ , and time constant is negligible, i.e.  $T_p \approx 0s$ . Then, maximum deviation of measured values from the model is -0.836%.

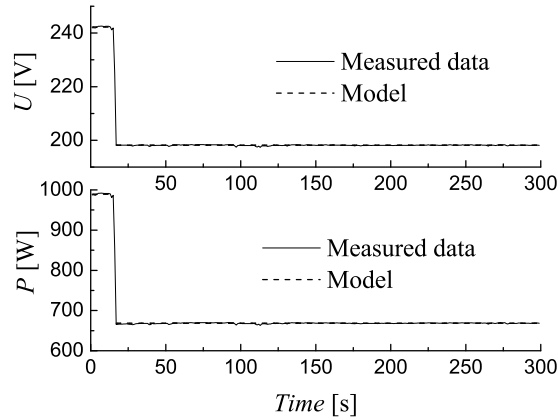


Fig. 3. Measured and simulated response of heater power to voltage step-down of 20%

Similar power response to step voltage change has incandescent lamp, but voltage exponents are smaller, they are  $\alpha_s \approx \alpha_t = 1.483$ . Exponential dynamic load model with these exponents and time constant  $T_p = 0s$ , models real power response to voltage change very well, because maximum deviation of measured values from the model is -0.403%.

Results of measurements during one voltage step-down experiment on mercury lamp (250W), as well as simulated real and reactive power responses, are presented in Fig. 4. Real power of mercury lamp changes with step voltage change and keeps its new value, so  $\alpha_s \approx \alpha_t = 2.441$  and  $T_p \approx 0s$ . Introducing these parameters in exponential dynamic load model yield maximum deviation of mercury lamp real power response to the voltage change from simulated response is 0.982%. On the other hand, reactive power of mercury lamp recovers after the voltage change. Thus, measured power response can be fitted quite well with the model whose parameters are  $\beta_s = 3.318$ ,  $\beta_t = 3.535$  and  $T_q = 102.17s$ , because correlation coefficient [8] is 0.973 and maximum deviation of measured values from the model is 0.811%. For better insight, Fig. 5 presents zoomed reactive power response of the

mercury lamp to the same voltage step-down and corresponding model.

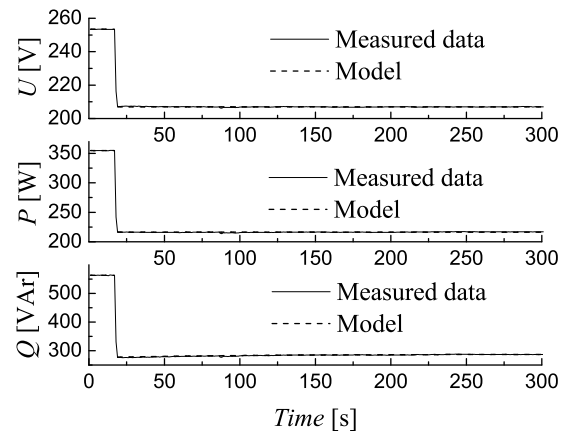


Fig. 4. Measured and simulated response of mercury lamp real and reactive power to voltage step-down of  $\approx 20\%$

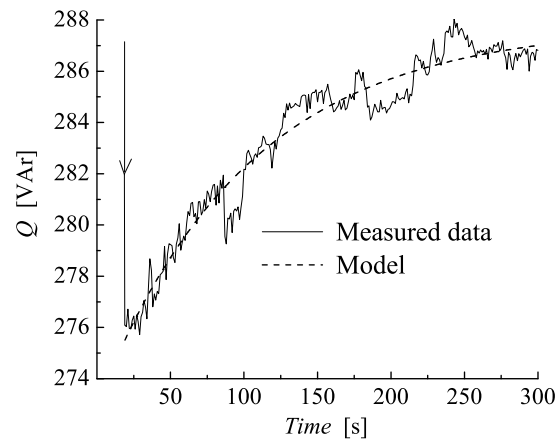


Fig. 5. Zoomed measured and simulated mercury lamp reactive power response to voltage step-down of  $\approx 20\%$

Experiments are also performed on another mercury lamp whose rated power is 125W. The results obtained from the same voltage change, step-up of 10% are mutually compared: identified parameters of 125W mercury lamp are  $\alpha_s \approx \alpha_t = 2.497$ ,  $T_p \approx 0s$ ,  $\beta_s = 3.327$ ,  $\beta_t = 3.565$  and  $T_q = 24.47s$ , while the parameters of

250W lamp are  $\alpha_s \approx \alpha_t = 2.389$ ,  $T_p \approx 0s$ ,  $\beta_s = 3.170$ ,  $\beta_t = 3.387$  and  $T_q = 43.41s$ . Voltage exponents  $\alpha_s$ ,  $\beta_s$  and  $\beta_t$  of considered lamps differ from each other 4.52%, 4.95% and 5.26%, respectively. Difference between reactive power time constants is much larger although both lamps belong to the same class of devices (outdoor lighting). Thus, reactive power time constant of 250W lamp is even 77.4% greater than corresponding time constant of 125W lamp.

Real power of fluorescent lamps similarly changes with the voltage change as real power of mercury lamp does it - “momentary” change its value and keeps it constant afterwards. Thus, on the basis of experiment, performed on the group of fluorescent lamps in one room, from Fig. 6, similar real power parameters are obtained to those for mercury lamp, i.e.  $\alpha_s \approx \alpha_t = 2.466$ ,  $T_p \approx 0s$ . Concerning these parameters maximum deviation of measured values from the model is -0.659%. On contrary, after voltage step-up reactive power of investigated fluorescent lamps continue to increase slightly (see Fig. 6). So, voltage exponent  $\beta_s$  of these lamps is greater than exponent  $\beta_t$ . In concrete case identified voltage exponents are  $\beta_s = 7.893$  and  $\beta_t = 7.388$  (more than two times greater than corresponding parameters of mercury lamps), while time constant is  $T_q = 63.72s$ . Fitting of reactive power response by the model with these parameters is very good because coefficient of correlation is 0.949, and maximum deviation of measured values from the model is less than percentile.

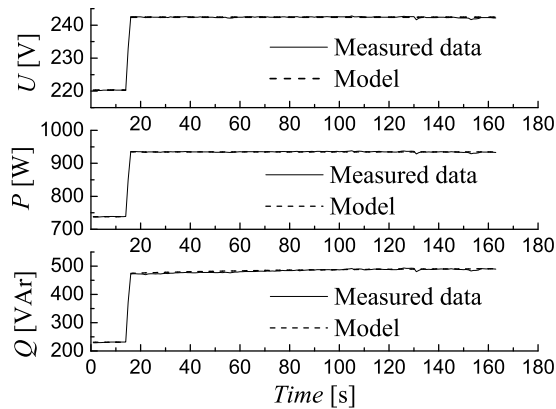


Fig. 6. Measured and simulated response of fluorescent lamps real and reactive power to voltage step-up of 10%

Characteristic of refrigerators is their *on/off* operation and relatively long transient after every beginning of *on* operation mode. Therefore, Fig. 7 presents the results of measurements during one experiment of voltage step-up during refrigerator

steady state operation conditions. Real power increases with voltage increase, and then oscillate around its new, average value with maximum deviation of 0.724%. Reactive power also changes with voltage and afterwards deviates at most 0.814% from its new average value. Thus, load model parameters of the refrigerator are  $\alpha_s \approx \alpha_t = 0.533$ ,  $T_p \approx 0s$ ,  $\beta_s \approx \beta_t = 2.506$ ,  $T_q \approx 0s$ .

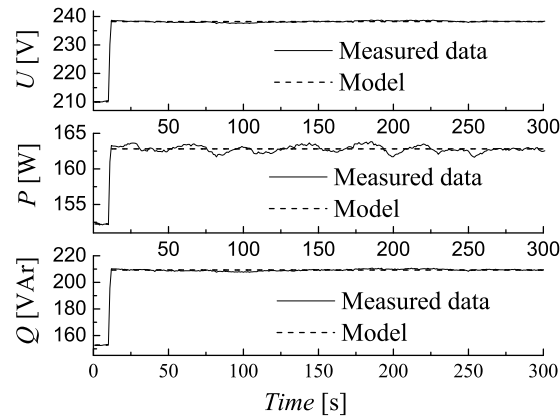


Fig. 7. Measured and simulated response of refrigerator real and reactive power to voltage step-up ( $\approx 15\%$ )

Experiments of the change of TV set supply voltage showed that its real power does not depend on voltage, while reactive power changes with voltage, approximately 0.3% for one percent of voltage change. After the voltage changes, both real and reactive power deviate from corresponding mean power value less than 5%.

Measurements during the change of induction motor supply voltage from  $U_n + 10\%$  to  $U_n - 10\%$  are shown on Fig. 8. Since, available data acquisition device has sampling rate 1Hz, fast electromagnetic transient is not captured, and identified exponential dynamic load model parameters are  $\alpha_s \approx \alpha_t = 0.219$ ,  $T_p \approx 0s$  for real power and  $\beta_s \approx \beta_t = 3.835$ ,  $T_q \approx 0s$  for reactive power. The model is good for long-term dynamic studies because maximum deviation of measured values from simulated power responses are -0.266% for real power and -0.928% for reactive power. All other numerous experiments on induction motor approve that exponential dynamic model is quite good because neither in one case percentile deviation of measured values from corresponding simulated power response is greater than 1%.



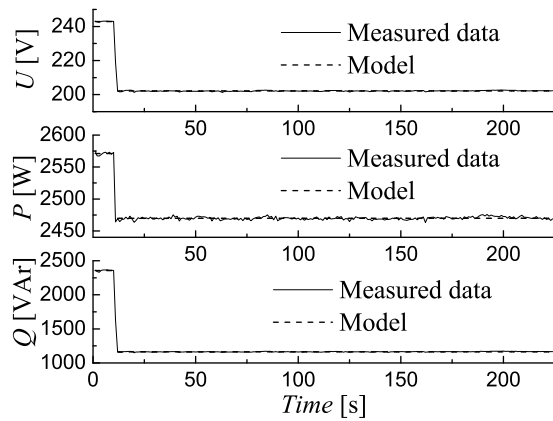


Fig. 8. Measured and simulated real and reactive power response of induction motor to voltage step-down of 20%

## 5 Conclusion

The paper presents some of the results of numerous laboratory tests on representatives of most frequently used low voltage devices in order to model long-term dynamic performance of these devices. It is found that exponential dynamic load model is adequate because maximum deviation of measured power responses from simulated responses is less than 1% for all devices except TV set where these deviations are somewhat larger, but still less than 5%.

Presented results show that identified parameters are quite different for devices belonging to different classes, i.e.  $\alpha_s$  and  $\alpha_t$  vary from 0 to 2.466,  $\beta_s$  and  $\beta_t$  from 2.506 to 7.893,  $T_q$  from 0 to 102.12s. Therefore, proper modelling of total load of a bus requires precise knowledge of load composition. Also, it is established that in some cases the parameters of devices which belong to the same class differ from each other significantly. Thus, it is recommended to continue this research to create one comprehensive data base of parameters of many low voltage devices as input data for load modelling by component-based approach.

## Acknowledgement

This paper is the result of the research connected with research and development project named "Load Diagram Characterization, Development of the Methodology for Energy Loss Calculation in Distribution Networks of EPS and Its Experimental Verification" financially supported by Ministry of Science and Environmental Protection, Republic of Serbia.

## 6 Appendix

Electric heater: type 3kWh,  $P_n = 3000$  W,  $U_n = 220$  V,  $f_n = 50/60$  Hz, EMI “JEDIN-STVO” - Bačka Palanka

Incandescent lamp: type A55,  $P_n = 100$  W,  $U_n = 230$  V, “PHILIPS” - Made in Poland

Mercury lamp:

1. type HPL-N 125 W, “PHILIPS” - Made in Belgium,

2. type HQL (MBF-L) 250 W, “OSRAM” - Made by Osram,

Fluorescent lamps: type L18W/10, Daylight,  $U_n = 220$  V,  $f_n = 50$  Hz, “OSRAM” - Made in Germany,

Refrigerator: type H728,  $P_n = 135$  W,  $U_n = 220$  V,  $f_n = 50$  Hz, “GORENJE” - Velenje

TV set: type Ei COLOR 55100 TXT,  $P_n = 65$  W,  $U_n = 220$  V,  $f_n = 50$  Hz, Made in Yugoslavia

Induction motor: type ZK90L2,  $P_n = 2.2$  kW,  $f_n = 50$  Hz,  $\Delta 380/Y220$  V,  $5.2/3$  A,  $\cos\varphi = 0.86$   $n_n = 2885$  min<sup>-1</sup>, “SEVER” - Subotica.

## References

- [1] J. R. Ribeiro and F. J. Lange, “A new aggregation method for determining composite load characteristics,” *IEEE Trans., Power Appar. Syst.*, vol. 101, no. 8, pp. 2869–2875, Aug. 1982.
- [2] P. Pillay, S. M. A. Sabur, and M. M. Haq, “A model for induction motor aggregation for power system studies,” *Elect. Power Syst. Res.*, vol. 42, no. 3, pp. 225–228, Sept. 1997.
- [3] L. Korunović and D. Stojanović, “Load model parameters on low and middle voltage in distribution networks (in serbian),” *Elektroprivreda*, no. 2, pp. 46–56, Apr./June 2002.
- [4] L. M. Hajagos and B. Danai, “Laboratory measurements and models of modern loads and their effect on voltage stability studies,” *IEEE Trans., Power Syst.*, vol. 13, no. 2, pp. 584–592, May 1998.
- [5] O. M. Fahmy, A. S. Attia, and M. A. L. Badr, “A novel analytical model for electrical loads comprising static and dynamic components,” *Elect. Power Syst. Res.*, vol. 77, no. 10, pp. 1249–1256, Aug. 2007.
- [6] D. Stojanović, L. Korunović, and J. V. Milanović, “Dynamic load modelling based on measurements in medium voltage distribution network,” *Elect. Power Syst. Res.*, vol. 78, no. 2, pp. 228–238, Feb. 2008.
- [7] D. Karlsson and D. Hill, “Modelling and identification of nonlinear dynamic loads in power systems,” *IEEE Trans., Power Syst.*, vol. 9, no. 1, pp. 157–166, Feb. 1994.
- [8] M. Merkle, *Probability and statistics for engineers and students of technical sciences (in Serbian)*. Beograd: Akademska misao, 2006.