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MEASUREMENT-BASED EVALUATION OF DISTRIBUTION TRANSFORMER LOSSES CHARACTERISTICS FOR SUSTAINABLE VOLTAGE REGULATION

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Abstract This paper presents the characteristics of distribution transformer losses obtained on the basis of field measurements in a distribution grid. The active and reactive powers were recorded simultaneously at both 110 kV and 35 kV transformer voltage levels in different periods of the days, when the position of the on-load tap changer was changed intentionally. The variations of total transformer losses during these experiments were modelled by exponential models. The parameters of the models were grouped according to the particular daily periods, analysed statistically and compared with corresponding parameters of transformer load models. The importance was emphasised of knowing transformer losses characteristics in the networks with a significant share of distributed generation, energy storage systems and electric vehicles.

Keywords
distribution transformer, measurements, losses, characteristics, sustainability, voltage regulation

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1 Introduction

Today, a large number of new load devices are used, and there is a need to determine both their characteristics and the characteristics of the aggregate load in which they participate [1]. In addition, there is a global trend of liberalisation of the electricity market, in which electricity becomes a commodity like any other. Under these circumstances, it is extremely important to know the precise consumption data, including data on which load model is adequate and the values of its parameters. These data are included as input data in various steady state and dynamic analyses of power grids and systems, and can be used both in their operation and planning [2]. The accuracy of the calculation results depends strongly on the accuracy of the input data, as stated in many references, such as [3].

In addition to the massive use of new load devices, modern power grids are characterised by the increasing use of distributed energy sources, energy storage systems and electric vehicles, which introduces new components to be modelled. For example, electric vehicles (EVs) in battery charging mode represent a load, but they can also be used as sources of electricity [4]. The unpredictability of electricity production from renewable energy sources (RESs) and the consumption/production of EVs, can lead to numerous problems in the operation of the electricity grid. Therefore, it is necessary to improve the control and protection of the grid, which, along with the infrastructure advances, lead to the emergence of smart grids [5]. One of the very important issues in the modern power grids is maintaining stable voltage levels, often called the sustainable voltage regulation. It ensures grid reliability, prevents equipment damage by managing the fluctuations caused by variable generation and demand, and improves energy efficiency, which represents one of the pillars of the sustainable energy transition [6].

For sustainable voltage regulation, the load-to-voltage characteristics of aggregate loads connected to the network buses are very important. These can be obtained by the measurement-based approach and the aggregation-based approach. The former is recommended, because the aggregation-based approach requires data on the model parameters of all load devices, as well as data on the aggregate load structure, which is very difficult to know precisely. The measurement-based approach implies field measurements carried out either during the experiments in an electric power system, or during the continuous system operation [7].

This paper is the continuation of the research [8], that deals with identification of the statistically reliable parameters of load-to-voltage characteristics of an aggregate load on the basis of experiments in a distribution network. Given that accurate models of transformers (and lines) are also important for network analysis, this paper deals with the modelling of distribution network transformer losses in terms of their dynamic responses to voltage changes.

2 Description of Measurements

Simultaneous measurements of the voltage and active and reactive powers were performed at the 35 kV and 110 kV levels of a 31.5 MVA transformer in the transformer substation TS "Niš 13", in the winter season. Two three-phase power analysers [9] were connected via the existing voltage and current transformers. Experiments of on-load tap changes were carried out on two weekdays in different periods of time: morning, afternoon and night, while each series of experiments consisted of 5 to 9 voltage changes, providing enough data for statistically reliable parameters of the transformer losses models. During the experiments, the average voltage, active and reactive power values were recorded by the analyser, each second.

The power losses of the transformer were obtained as the difference of the measured powers on its primary and secondary sides. They were analysed, and subsequently modelled with adequate models. In all the considered operating regimes, the active power losses ranged from approximately 0.112 MW to 0.163 MW, and were of the order of magnitude of the percentage of active power measured at the transformer primary. The reactive power losses were significantly higher, and ranged from 0.841 Mvar to 1.491 Mvar, which, on average, amounted to slightly more than a quarter of the reactive power recorded at the 110 kV transformer level.

3 Applied Models

Figure 1 depicts the active power losses of the transformer during two consecutive experiments of changing the transformer ratio in the (weekday) evening. The active power losses change with the voltage, but the influence of stochastic load changes are so large that the attempt to fit the measured values with the exponential dynamic model described in [10] gave very small correlation coefficients, about 0.1, for both consecutive responses. Similar values of the correlation coefficient were obtained for other responses of active power losses. Taking into account the variations of active power losses even when the voltage was almost constant, the average values of the losses were considered, and the losses were modelled with the exponential static model in the form:

$$\Delta P = \Delta P_0 \left(\frac{U}{U_0} \right)^{\alpha_s} , \tag{1}$$

where: ΔP and ΔP_0 represent the average values of the active power losses after and before the voltage change, respectively; U and U_0 are the average voltage values at a 35 kV voltage level after and before the voltage change; and α_s is a steady state voltage exponent of the active power losses. This exponent is denoted commonly as k_{pu} in an exponential static load model [7]. From the two experimental data in Figure 1, α_s =1.03 and α_s =0.73 were obtained, respectively.

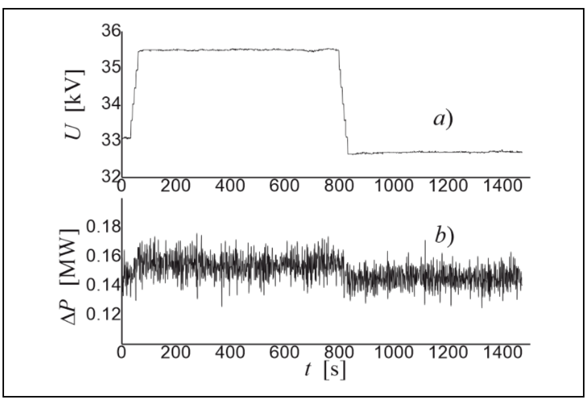

Figure 1: Voltage at the 35kV level a), and transformer active power losses b) during two consecutive experiments

The analysis of reactive power losses showed that the losses change simultaneously with the voltage and recover after these changes. It was found that reactive power losses can be modelled by an exponential dynamic model during all the examined voltage changes, with a correlation coefficient greater than, or equal to 0.7. For illustration, Figure 2 depicts: the voltage changes on the secondary side of the transformer during the experiments from Figure 1, and the corresponding responses of the reactive power losses to these changes. The same Figure also presents the fitted curves in the form:

$$\Delta Q(t) = \left(\Delta Q_0 \left(\frac{U}{U_0} \right)^{\beta_s} - \Delta Q_0 \left(\frac{U}{U_0} \right)^{\beta_t} \right) \cdot \left(1 - e^{-t/T_q} \right) + \Delta Q_0 \left(\frac{U}{U_0} \right)^{\beta_t} . \quad (2)$$

In (2), the previously not mentioned variables and parameters are: $\Delta Q(t)$ and ΔQ_0 – reactive power losses in the time domain during the experiment, and the initial value of the reactive power losses before the voltage change, respectively; T_q – the recovery time constants of the reactive power losses, β_s – the steady state voltage exponent of the reactive power losses, β_t – the transient voltage exponents of the reactive power losses. The identified parameters of model (2) on the basis of two consequent experiments, are: β_s =0.53, β_t =1.17 and T_q =143.7 s; and β_s =0.71, β_t =1.26 and T_q =54.9 s, respectively.

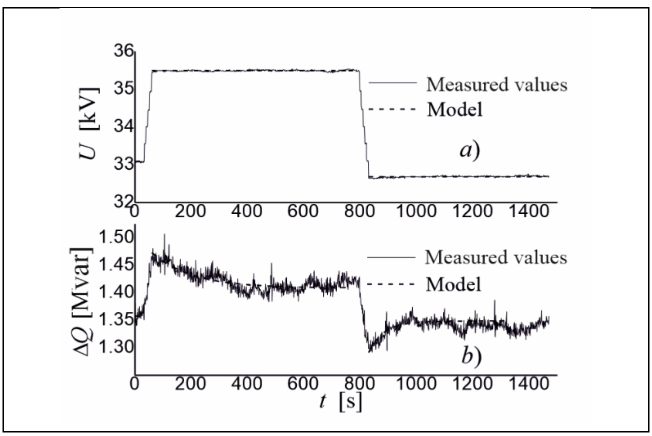

Figure 2: Voltage at the 35kV level a), and reactive power losses of the transformer b), during two consecutive experiments, together with the corresponding model

4 Characteristics of Active and Reactive Power Losses

Models (1) and (2) were used for modelling of active and reactive power losses, respectively, during all the performed experiments of voltage changing on two weekdays, in the morning, afternoon and evening. It was found that they depend on the operating regime of the transformer. A statistical analysis of the identified α_s values yielded the following average values: 0.59, 0.20 and 0.94, in the morning, afternoon and evening, respectively. Regardless of these differences, a general conclusion can be drawn that this parameter active power losses is smaller than the corresponding α_s parameter of total transformer load at the 35 kV level, in the same (winter) season. These parameters are: 1.20 in the morning, 1.19 in the afternoon and 1.25 in the evening [8]. However, the influence of active power losses characteristics on the behaviour of the total load at the 110 kV level can be neglected, since, as mentioned, the transformer active power losses are very small in comparison with the active power at the 110 kV level. In general, the characteristics of active power losses have a minor influence on the load-to-voltage characteristics of the load at higher voltage levels, and, consequently, will have almost no effect on the future grids with significant generation from RESs, with energy storage systems (ESSs), as well as numerous EVs connected to the network and operating as consumers/sources of energy.

Table 1: Parameters of the exponential dynamic model of: reactive power losses and reactive transformer load at 35 kV and 110 kV, in different daily periods during the winter season

	Morning	Afternoon	Evening
β_s	0.71	0.64	0.78
β_{s_35}	4.43	4.99	4.16
β_{s_110}	3.49	3.87	3.15
β_t	1.38	1.26	1.31
β_{t_35}	4.79	5.30	4.62
β_{t_110}	3.93	4.29	3.62
T_q [s]	172.8	134.9	134.2
T_{q_35} [s]	136.8	117.7	80.2
T_{q_110} [s]	133.5	124.7	89.6

Table 1 lists the average values of the exponential dynamic model of reactive power losses – β_s, β_t, and T_q, identified in different daily periods: morning, afternoon and evening. For comparison, the parameters of the total reactive load of the transformer at the 35 kV level, β_{s_35}, β_{t_35}, and T_{q_35}, and these parameters of the total reactive load at the 110 kV level (β_{s_110}, β_{t_110} and T_{q_110}), all obtained in the winter season, are also presented in Table 1.

It can be noted that the values of β_s , and β_t that characterise the reactive power losses, are much smaller than the corresponding values of the parameters of the reactive transformer load at the 35kV level. Thus, the characteristics of reactive power losses result in smaller values of β_{s_110} and β_{t_110} in comparison with β_{s_35} and β_{t_35}. Similarly, larger values of the recovery time constants of reactive power losses than the time constants of a reactive load at a 35 kV voltage level, cause the decrease of recovery time constant at the 110 kV level. Therefore, the characteristics of transformer reactive power losses should be included in both static and dynamic analysis of electric power networks. They influence the load-to voltage characteristics of the transformer load at its primary, and, therefore, the obtained characteristics of transformer reactive power losses should be included in the voltage regulation problem.

5 Conclusion

The analysis of the variations of total transformer losses during the experiments of transformer ratio changes showed that the active and reactive power losses can be modelled by exponential static and an exponential dynamic model, respectively. The parameters of the model of active power losses were obtained and analysed in different daily periods. It was pointed out that they do not affect the characteristics of active power load of the transformer significantly. On the other hand, the characteristics of reactive power losses decrease both steady state and transient voltage exponents notably, and recovery time constant, of total reactive load at the transformer primary. Therefore, the dynamic characteristics of reactive power losses of distribution transformers should play an important role in modelling aggregate distribution loads for different purposes, including sustainable voltage regulation in networks with RESs, ESSs and EVs.

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Lidija M. Korunović received her Dipl.Ing., MSc and PhD degrees from the Faculty of Electronic Engineering - University of Niš (UNI-FEE), Serbia. She is a full Professor at the same Faculty. From 2016 to 2023 she was the Head of the Department of Power Engineering at the UNI-FEE. The main areas of her research are load modelling, power quality and distribution systems. Lidija M. Korunović has published more than a hundred scientific papers in international and national journals and conference proceedings, two memoirs, two textbooks, two technical solutions and two technical reports, which are the results of her membership in two CIGRE/CIRED working groups. She took part in ten scientific projects and studies supported by the Serbian Ministry of Science. She is the team leader of the TRANSIT project (funded by the EU) within UNI-FEE.

Povzetek v slovenskem jeziku

Merilno podprta analiza značilnosti izgub distribucijskih transformatorjev za trajnostno regulacijo napetosti. Članek obravnava značilnosti izgub distribucijskih transformatorjev, določene na podlagi terenskih meritev v distribucijskem elektroenergetskem omrežju. Aktivna in jalova moč sta bili sočasno merjeni na transformatorskih napetostnih nivojih 110 kV in 35 kV v različnih obdobjih dneva, pri čemer je bil položaj obremenitvenega preklopnika (OLTC) namerno spreminjan. Spremembe skupnih izgub transformatorja med izvedenimi preizkusi so bile modelirane z eksponentnimi modeli. Parametri modelov so bili razvrščeni glede na posamezna dnevna obdobja, statistično analizirani ter primerjani z ustreznimi parametri modelov obremenitve transformatorja. Poudarjen je bil pomen poznavanja značilnosti izgub transformatorjev v omrežjih z velikim deležem razpršene proizvodnje, sistemov za shranjevanje energije in električnih vozil.