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The Use of DigSilent Power Factory Simulator for "Introduction into Power Systems" Lectures

Victor Astapov* (*Researcher, Tallinn Technical University, Tallinn, Estonia*),
Ivo Palu (*Professor, Tallinn Technical University, Tallinn, Estonia*),
Toomas Vaimann (*Senior Researcher, Tallinn Technical University, Tallinn, Estonia*)

***Abstract* – The first-year students at the technical universities often face the problem of using the previously acquired knowledge at a higher level required by engineering education. To solve this problem, the authors developed a series of lectures dedicated to establishing theoretical background, based on simulations in DigSILENT Power Factory software. In the lectures, the physical values and quantities as well as the purpose and characteristics of the power equipment are explained on the example of the simple models.**

This article includes the detailed description of a lesson "Introduction into Power Systems" and presents some models and ways of explaining the material. The sections below concentrate on the lecture format focusing on methods for explanation of physical quantities and introducing power system components. Sequential parts create the mosaics of grid, with the following description of basic laws and principles in power systems.

***Keywords* – DigSilent; Engineering education; Power system simulation.**

I. Motivation and Background

Nowadays young people turn to computer technologies with more pleasure than to books. Nevertheless, presentations with slides receive less attention than it should be. In 2007, more than 50 % of university freshmen responded that they like to study through videogames and simulators [1]. The authors decided to exploit the benefits from this interest and to start using DigSILENT "PowerFactory" software (further – PowerFactory) [2] during the lectures for the first year students and practical lessons for the second year students. The state-of-the-art for modeling and simulation has been developing in the last 30 years [3], and nowadays there is plenty of software meant for the solution of different engineering problems. Many simulators are installed in universities not only as a research, but also as an educational tool.

On the other hand, according to the statistics of "IEEE Transactions on Power Systems", the journal published only 49 education papers in the period from 2004 to 2013 and only some of them are related to software [4]. PowerFactory is already implemented in the Technical University of Denmark, where test model of grid with loads, local wind generators and offshore farm was presented [5]. However, this particular paper and research presented in other articles focus on simulations through practical classes or simulation as an independent work for the students with background in power engineering [6], [7]. In our case, simulations are performed during the lecture, the focus group is university freshmen and the material covers the knowledge of physics at the secondary school level and includes some university introduction classes.

According to gymnasium (high school) curriculum in Estonia, pupils should have general understanding of electromagnetics [8]. They must understand the main electrical parameters and laws such as alternating current, full power, induction, Ohm's law for parallel and series circuits, etc. The problem lies in the application of this knowledge. Students generally know what resistance means, but most of them do not know how it works in electrical power lines and what its actual effect on the power system is. Many physical quantities are quite difficult to understand before seeing the simulation, where through changing of one parameter, it is possible to observe the effects on other power system elements. If students realize this clearly, it is easier to explain how the entire system works. As a next step, modeling of the whole power system lets students comprehend how the elements interact with each other. At the final stage, the interconnection of neighboring power systems may be presented. After this, the whole chain starting from impedance and resistance becomes clear and students know how physical parameters influence the power system and the processes inside and outside it. In this article, the authors share their experience and reflect on the models used during the lectures.

II. Lectures Format

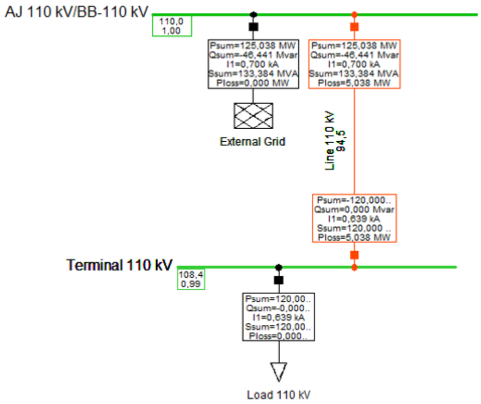
The idea of the lectures is to build a simple typical power system in PowerFactory and to introduce the main ideas of power engineering and explain the processes inside the system elements. In the simulation process, several decisions and approaches are introduced. Some of them purposefully present an erroneous situation, explaining to students how to prevent it by taking the right engineering decision. Some of the models have two correct solutions with an aim to show the variability of modeling.

Some lecture slides with theoretical content, initial data for simulation and the screen shots of PowerFactory simulator windows are presented in the figures later. The part of a slide with representation of electrical power line is shown in Fig. 1 as an example. The simple model consists of two busbars 110 kV; one has an external power source, another – a load. The note about what parameter needs attention is also given at the bottom. From simulations, students can see that the power line generates reactive power that should be consumed.

* Corresponding author.
Email: victor.astapov@taltech.ee

1. Active and reactive power

Model 1
External grid. Nominal voltage $U_1 = 110$ kV.
Cable length $l_1 = 100$ km, area (cross-section) $A_{1\text{line}} = 500$ mm^2.
General active load $P_{1L} = 120$ MW.



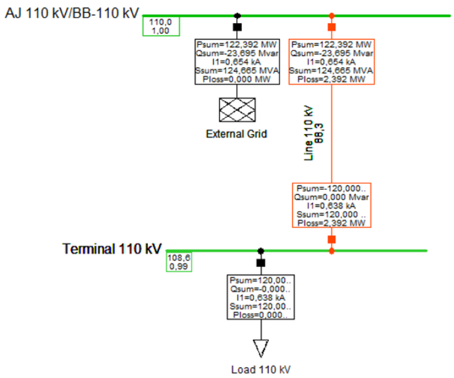
Pay attention *to full power, which consists of active and reactive power. No reactive load, but we need to consume it.*

Fig. 1. A part of a slide presenting an electrical power line.

At the lecture, most of the slides were presented together with live simulations in PowerFactory. This allows observing parameters of the system in the result boxes placed next to each element. The cases including different systems and equipment were prepared in advance and saved with the help of "operation scenario" and "network variations" options [9]. This gives the opportunity to switch cases as fast as needed, makes the discussion more intensive and less boring. After simulations are made, the students are again asked to pay attention to the parameters that have changed in the result boxes of the equipment (Fig. 2).

2. Line resistance. Length of line

Model 2
Changes in: line length up to $l_2 = 50$ km
External grid. Nominal voltage $U_2 = 110$ kV.
Cable length $l_2 = 50$ km, cross-section $A_{2\text{line}} = 500$ mm^2.
General active load $P_{2L} = 120$ MW.



Pay attention *that active power losses reduced almost twice.*

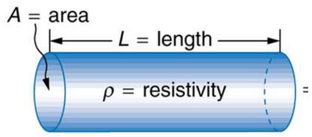
Fig. 2. A part of a slide with the model in PFS for the explanation of line resistance.

Then, the students may offer their explanation of why this parameter changed and discuss it. After this, the slide with theory follows, where the formula explains the dependence of one parameter on another (Fig. 3). The line resistance depends on resistivity, cross section and length. The students understand that the length and cross-section of conductor changes not only resistance, but also power losses.

2-3. Line resistance

$$R = \frac{\rho_0 l}{A_{line}};$$

R – resistance of conductor, Ω;
ρ_0 – resistivity of material, Ω m;
l – length of conductor, m;
A_{line} – cross section of conductor m^2.



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$$\Delta P = \frac{P^2 + Q^2}{U^2} R$$

ΔP – active power losses in conductor, MW

Fig. 3. A part of a slide with explanation of resistance and active power losses.

They can observe it considering the numbers in the simulation boxes. The whole lecture goes further in the similar manner: model – simulation – explanation.

III. Representation of Physical Parameters

In this part, we will introduce the way of representing physical parameters and power engineering definitions, their associativity, and their influence on the power system performance. The students are shown that narrow electric line sometimes cannot carry the required load. From the simulations, the students find that the line may be overloaded. The definition of line capacity is presented. At the same time, the problem of minimization of losses and minimization of costs (i.e. optimal cross-section of electric line) is addressed.

The voltage drop is also introduced. Changing the load during simulations, it is also possible to show how voltage drop changes along. Considering example (1) it is explained that the larger amount of power is transferred, the more voltage drops [10].

$$\Delta U = \frac{PR + QX}{U_{\text{nom}}}, \tag{1}$$

where ΔU – voltage drop, %; U_{nom} – nominal voltage, V; R – resistance of conductor, Ω; X – reactance of conductor, Ω.

Then, the nominal voltage of power line is reduced from 110 kV to 35 kV. The simulation shows that the power flow cannot be ensured because of the huge voltage drop and power losses. The students are asked why this happened and what should be changed to fix this problem. They need to use (1) introduced above (several minutes before this question). The reduction of resistance (i.e. increase of the cross-section or decrease of length) leads to the reduction of power losses and voltage drop. This is the explanation of transmission, distribution lines and power system structure: the shorter the distance and the amount of power, the lower nominal voltage of electric line is. In Estonia, the nominal voltage of transmission lines is 110 kV to 330 kV, of distribution lines – 6 kV to 35 kV [11].

The definition of the transformer is presented to the students. Now they can understand the reason why transformer is used in the power system. The main types and their functions are introduced. Special attention is paid to efficiency and capacity. The analogy with electric lines is drawn. Mostly, the transformers with bigger capacity have smaller power losses in terms of similar load, but tend to be more expensive.

The next model consists of 6 kV busbar with an external power source, the transformer 6/0.4 kV with capacity 400 kVA, and the low voltage busbar with load. This case focuses on reactive power and cos φ problem. At first, the power flow is performed for only active power load equal to 350 kW and cos φ = 1. Then cos φ is changed to 0.95, the simulations demonstrate that the transformer is overloaded (Fig. 4). The main consumers of reactive power and possibilities of reactive power compensation can be discussed.

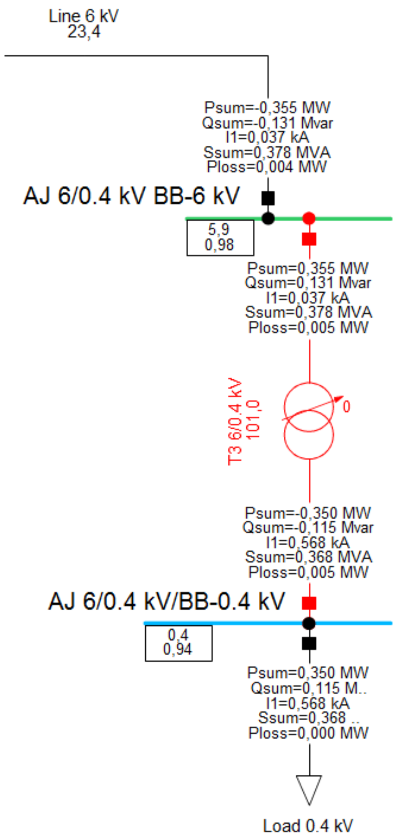

Fig. 4. PFS demonstrating the influence of reactive power on the equipment capacity.

IV. The Power System Mosaic

In the previous chapter, the approach to describing the main physical parameters and power system elements has been shown. In this part, we introduce power systems.

The typical structure of a power system (generator – transformer – transmission line – transformer – distribution line – transformer – line – load) is presented as a model in PowerFactory, as well as a scheme on the slide (Fig. 5).

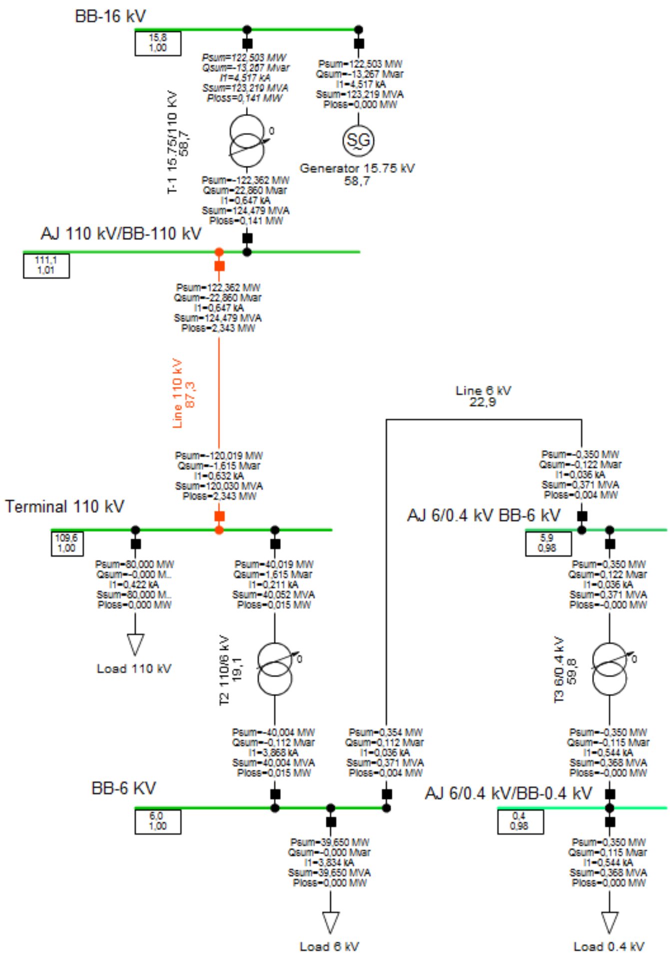

Fig. 5. The model of a power system.

Students are asked to pay attention that the generation output P_G = 122.503 MW of the system with different voltage level is lower than the input of external power grid P_E = 122.392 MW (Fig. 2) with the same loads and only one 110 kV electric line.

After this, the additional electric line 110 kV between AJ-110 kV and Terminal-110 kV is added to explain the reserve requirements. Through the construction of the second line, the equipment costs increase, but power losses decrease: the generator output is P_G = 121.901 MW compared to P_{G2} = 122.508 MW. In addition, a very important aspect is brought to the fore that the system is insured in case of unexpected power failures or fixed-schedule maintenance. In PowerFactory, one of the lines is switched on and the capability of the second line to carry full load is shown. The analogy with transformer and other equipment is also drawn.

The voltage control in the system is also explained with the help of simulations. Changing the tap in transformers T-1, T-2, and T-3 and performing power flow creates the situation when the voltage at busbar 6 kV reduces below the norm (5.7 kV), but at busbars 110 kV and 0.4 kV it stays normal.

The influence of asymmetrical loads is also investigated. For this reason, at busbar BB-6 kV the load 39.65 MW is split into phases: $P_A = 8$ MW; $P_B = 8$ MW, and $P_C = 23.65$ MW. As a result, the students observe the generator output (Fig. 6).

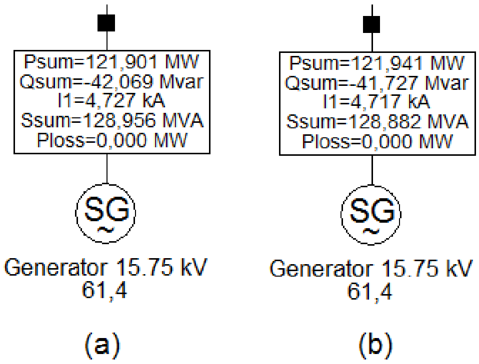

Fig. 6. The influence of asymmetrical loads: symmetrical (a), asymmetrical (b).

The simulations show that the difference in active power is about 40 kW. Despite the small difference in power, the yearly economy of nearly EUR 5,045 per year could be achieved. For the calculations, the price of 0.0144 EUR/kWh for 6 kV level in Estonia was taken [12]. The effect of unbalanced loads in low voltage level is more significant, because the price in this case is about 0.0482 EUR/kWh [13].

The next step is the connection of the set of wind turbines with total installed capacity of 10 MW to the bus 6 kV. After performing the power flow, the output of generator is $P_{G+W} = 111.608$ MW and $Q_{G+W} = -44.738$ Mvar. Comparing with the model without wind park $P_G = 121.901$ MW and $Q_G = -42.069$ Mvar, it can be seen how active power losses of the system are reduced and this system needs less reactive power compensation. The explanation of distributed generation follows. On the same example, the simplified equation of power balance (2) is presented and explained [14].

$$\sum S_G = \sum S_{LD} + \sum S_{PL}. \quad (2)$$

where ΣS_G – sum of generated power, ΣS_{LD} – sum of load demands, ΣS_{PL} – sum of power losses.

The small overview of power system interconnections is given to the students. The main principles, technical and economic aspects, as well as pros and cons are presented. The basics of electricity market are described.

A very important issue of generation costs is also presented. The students acquire knowledge about the main expenses of electricity production: capital, operational and maintenance, emission, and fuel costs [15], [16]. The meaning of the last one is easy to explain with the help of PowerFactory, which can include the fuel cost characteristics for simulations. For the main generator, one of the set of fuel characteristics is defined. Two simulations with and without wind turbines are performed. The result boxes in both cases are shown in Fig. 7.

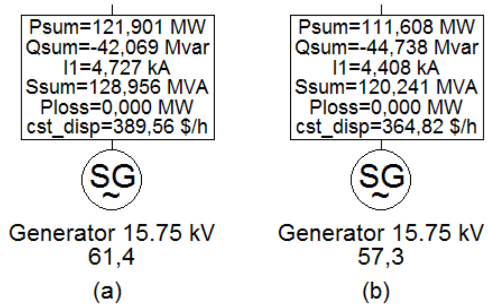

Fig. 7. The influence of wind generation on fuel costs: without wind park (a), with wind park (b).

The generation of active power in the model without wind park is $P_G = 121.091$ MW and the costs are *cst_disp* = 389.56 USD/h. With wind park, generator output and cost of one hour of operation are reduced. However, the price for 1 MWh in the first case is $C_G = 389.56$ (USD/h) / 121.901 (MW) = 3.20 (USD/MWh); in the model with wind park, this price is C_{G+W} = 364.82 (USD/h) / 111.608 (MW) = 3.27 (USD/MWh). Generally, more loaded generating units of thermal power stations have better fuel consumption efficiency [17], that is why wind power sometimes surpasses the cost of the electricity generated from thermal power plants in closed loop.

V. Conclusion

This article presents the materials for the series of lectures “Introduction into Power System” and the approach, where engineering simulator is used for explanations. The aim of the interactive classes is to present power system concepts for university freshmen in an interesting and understandable way.

The objective of the method is to help students comprehend the power system and the meaning of parameters through visual observation and explanation of the processes with theory in the background. During practical classes with simulator software, the students usually solve some particular tasks. In our case, they can put in order or refresh the knowledge they need. At the same time, they are also introduced into engineering software.

The lesson structure allows introducing or reminding about the main physical parameters in a logical chain, one by one. The simulation models let observe the results of changes and make materials more logically structured and easy to understand. The work with simulator can be considered a game, which makes the lecture more positive and involving. This is because the students can see the results immediately, compare the models and analyze the changes these models bring to the systems. It is an important educational effect, which facilitates acquisition of the material and enhances the students’ involvement in the engineering sciences.

One of the authors delivered these lectures and the subsequent feedback of the students demonstrated a positive effect of software implementation. Twenty-five students participated in the survey and they were asked four questions. The results are presented in Table I.

TABLE I

THE RESULTS OF SURVEY AFTER THE LECTURE
("0" – MINIMUM, "5" – MAXIMUM GRADE)

The number of the question	Average evaluation
1. How can you evaluate your knowledge about Power Systems before the lecture?	1.60
2. Please, rate the material presented during the lecture	4.12
3. Please, evaluate your knowledge about Power Systems after the lecture	3.12
4. How would you rate your support for using simulators in the learning process?	4.04

This proves that this kind of material is easier to understand and remember due to the visualization of processes, which occur in real power systems.

We need to admit that PowerFactory allows conducting interesting practical classes. Simulations have already been included into the course "Distributed Generation". The students were able to create their own local grid, supply own houses, install renewable energy sources, etc. The lessons helped them understand that this installation leads to other changes in the grid and possible additional investments. For instance, it shows that it is not enough to install a wind generator and produce electricity for free. This kind of simulations motivates students to be accurate in calculations and creative in their research.

The course in general has been positively evaluated, the students' feedbacks showed their positive impressions about the classes. 16 students registered for the exam, 13 of them passed with the average grade 4.15. PowerFactory was used in the development of one Master and two Bachelor papers. TalTech School of Engineering will continue educating students using this software and other power engineering simulators. This topic is going to be covered by authors in the nearest future.

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Victor Astapov was born in Vitebsk, Belarus, in 1979 and received his first M.Sc. from Vitebsk State University, Belarus in 2001 as a teacher of Mathematics and Physics. He received MSc and PhD degrees in electrical engineering from Gomel State University, Belarus and Tallinn University of Technology, Estonia, in 2007 and 2015 respectively. In 2017–2018 he was a post-doctoral researcher in KTH Royal Institute of Technology, Stockholm, Sweden.
He is currently a Researcher in Tallinn University of Technology, Department of Electrical Power Engineering and Mechatronics. He has been working as a Dispatcher in distribution networks in Belarus and as an Electrical Engineer in several Russian companies. His main research interest is the power system analysis and integration of renewable sources into power grid.
Email: victor.astapov@taltech.ee

Ivo Palu was born in Rakvere, Estonia, in 1979. He graduated from the Tallinn University of Technology and received Ph.D. degree in electrical power engineering in 2009.
Currently he is Professor and Director of Department of Electrical Power Engineering and Mechatronics at Taltech. His subject of teaching is wind energy and electrical materials. His field of research is wind turbine co-operation with thermal power plants and grid integration of new energy sources. He is a member of the board of Estonian Society for Electrical Power Engineering and member of IEEE.
Email: ivo.palu@taltech.ee

Toomas Vaimann was born in Pärnu, Estonia, in 1984 and received his B.Sc., M.Sc. and Ph.D. degrees in electrical engineering from Tallinn University of Technology, Estonia, in 2007, 2009 and 2014 respectively.
He is currently a Senior Researcher in Tallinn University of Technology, Department of Electrical Power Engineering and Mechatronics. He has been working in several companies as an Electrical Engineer. He is the member of IEEE, Estonian Society of Moritz Hermann Jacobi and Estonian Society for Electrical Power Engineering. His main research interest is the diagnostics of electrical machines.
Email: toomas.vaimann@taltech.ee
ORCID ID: https://orcid.org/0000-0003-0481-5066