Automatic Integration of a Dynamic Security Assessment System into a Power Grid

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***Abstract*—Today's power grids must utilize more energy than they were originally planned for. Hence, they are slowly reaching their stability limits and that causes an increased risk of blackouts in electrical networks. To avoid such critical situations in the control room the system dynamic state must be assessed as quickly as possible and its personnel have to react to it early enough. This kind of evaluation could be done by the so-called Dynamic Security Assessment system which is able to assess the dynamic state of the electrical network online. This paper presents completely automatic methods of the dynamic security assessment system integration into a power grid, functionality testing of the Over Excitation Limiter (OXL) - which is implemented in the Automatic Voltage Regulator (AVR), and the electrical grid plausibility check.**

Keywords- dynamic stability; dynamic security assessment (DSA); transient security assessment (TSA); voltage security assessment (VSA); index; Over Excitation Limiter; network plausibility; power grid; contingency

I. INTRODUCTION

Worldwide the continuous increase of energy demand in the power grids has led to their strong overloading and rapid growth. The demand of electrical grids is expected to grow by approximately 50% by 2030 [1]. Today's transmission systems are based on the static or planning stability studies, which often do not consider some dynamic stability problems enough[2]. Therefore, these systems are unfortunately not designed for the future loads. Besides, the electrical grids are already very close to the limits of their transmission capacity, which is not only determined by the thermal limits, but more often by dynamic stability limits. Hence, over the years there have been more frequent unexpected operating situations such as black- and brown outs caused by poor system connections and overloading of the network elements. Another reason of the increased stress in the power grid is utilization of the decentralized renewable energy sources which can cause unexpected power flows in the electrical system [3]. Hence, good observation of the electrical network state has become a very important task for all network operators.

The security of the power systems can be determined from the load change, the generator application and existing limitations. The standard static stability analysis "Static Security Assessment" (SSA) which is usually used by the network operator is not always able to consider all major state changes in the transmission electrical system. Hence, SSA only estimates the power grid static situations and disregards the dynamic stability. However, to ensure full power grid security the network dynamic behavior should be also taken into account. So-called "Dynamic Security Assessment" (DSA) methodology is able to perform this task. It is able to observe power grids in a more detailed way and improve the network state evolution. The DSA system compares the power network dynamic stability in the current state without contingency to the same state with different contingencies. It estimates dynamic stability limits of the power grid, monitors the general system state and provides detailed information about the electrical grid. This system is able to observe the large complex power grids which include control equipment (e.g. HVDC), protective devices etc. [4].

In this work, new concepts for automatic integration of the DSA system into a power grid and for conducting a network plausibility check are introduced. In addition, the testing procedure for the Over Excitation Limiter (OXL), which is implemented in the Automatic Voltage Regulator (AVR), is described.

II. DSA SYSTEM INTEGRATION INTO A POWER GRID

Dynamic instabilities in power grids are mostly caused by some transient and voltage problems. Hence, Dynamic Security Assessment (DSA) is classified as Transient Security Assessment (TSA) and Voltage Security Assessment (VSA).

A. Transient Security Assessment (TSA)

Transient stability or rotor angle stability refers to the ability of the electrical network system to maintain its synchronism during an unexpected disturbance such as line or generator outages, short circuit, etc. [5], [6]. As a reaction to such disturbances, the synchronous generators could significantly change their rotor angels which in turn may lead to power system instability and blackouts [6].

To evaluate network transient stability after some contingency the different indicators or so-called indices could be used in a TSA system. Such indices assess the post-fault state of the power grid and provide information about a relative distance to the critical network state [9]. Several TSA indices are described in the literature [6].

For example, the Angle Index (AI) is often mentioned in literature and is defined as a minimum between 1 and the maximum ratio of the maximum load angle of the i-th generator and the maximum admissible load angle given by the protection relay (1) [6] [9].

Therefore, the protection relays of the generators limit the generator load angle (δ_i) to a certain value (e.g. 120°) [6].

$$AI = \min\left\{1, \max_{i=1,..NG}\left(\frac{\delta_{ci,\max}}{\delta_{c,\max,adm}}\right)\right\} \quad (1)$$

B. Voltage Security Assessment (VSA)

Voltage system stability refers to the ability of the electrical network system to maintain steady state voltages at its bus bars during unexpected disturbances or to maintain the equilibrium between generation and consumption of the energy in the power grid [5], [6]. Therefore, there could be large bus bar voltage deviations in the power system that cause load and generator loss thereby tripping the different network elements etc. [10].

Normally the loads are voltage- and frequency-dependent [11]. The following static load models are typically used for the power grid simulations [12]:

- constant impedance (Z),
- constant current (I),
- constant power (P).

Usually, to be closer to the real power grids, a mixture of these load models (the ZIP load model) is used for the electrical network simulations. The following mathematical formulas describe this load [14]:

$$P_L = P_0 \cdot (\frac{U}{U_0})^{\alpha_U} \cdot (\frac{f}{f_0})^{\alpha_F} \quad (2)$$

$$Q_L = Q_0 \cdot (\frac{U}{U_0})^{\beta_U} \cdot (\frac{f}{f_0})^{\beta_F} \quad (3)$$

For VSA, the frequency dependency must not necessarily be taken into account. Therefore, it was chosen for the simplification of calculations within this work.

Hence, active and reactive powers are determined as the product of the rated powers and ratio of actual and rated voltages. When the α and β factors are 2 the load is represented as constant impedance type, when they are 1 – as constant current and when 0 – as constant power [14].

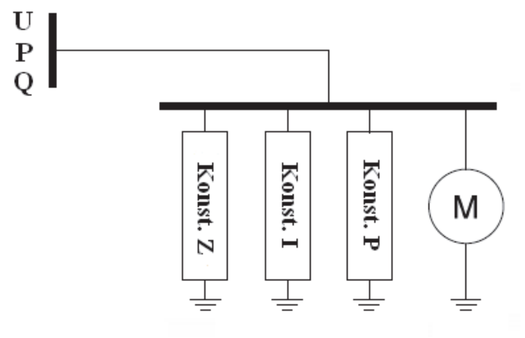

Figure 1. ZIP load model with an asynchronous motor [15]

Nevertheless, ZIP the model describes only the static behavior of the loads. Therefore, for considering the dynamic load behavior and, accordingly, for more accuracy of the network simulations, an asynchronous motor was included in the load model within this work. Figure 1 shows this load model. $\alpha + \beta = \chi$. (1) (1)

In addition, to assess the network dynamic stability different indices could be used in a VSA system.

C. Concept of automatic integraton of a DSA System with a power grid

The different DSA indices, such as Angle Index (AI), Maximum Frequency Deviation Index (MFDI), Frequency Recovery Time Index (FRTI), Dynamic Voltage Index (DVI) etc., and the simulation models, such as the ZIP load model with asynchronous motor, all belong to standard models of PSS®NETOMAC.

The PSS®NETOMAC [12] is a power system simulator for electro-magnetic and electro-mechanical transients with an open modelling interface BOSL for the implementation of user defined macros. These user defined models can be provided as asci text files which are then immediately compiled by PSS®NETOMAC. Such files for the integration of the already mentioned DSA standard models into a power grid are automatically created by the MATLAB routines which are developed in the scope of this work. The concept of these routines are shown on the Figure 2.

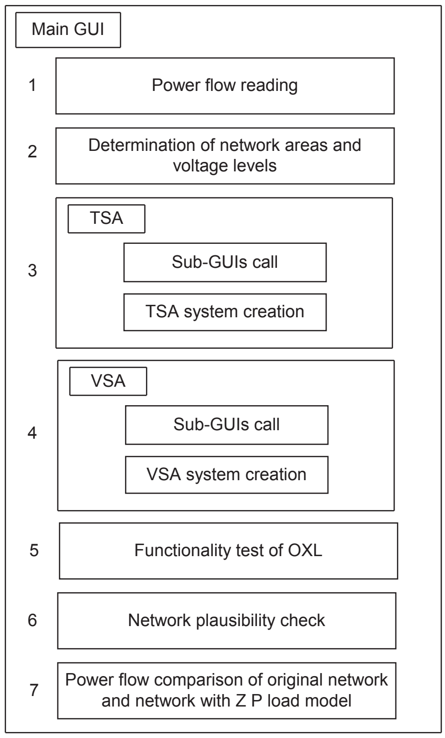

Figure 2. Concept of the developed MATLAB routines

First, the main Graphical User Interface (GUI sets the main function, which reads the load flow results of the original network model and sends this data for later use to the main GUI. In the main GUI different areas and voltage levels of the power grid model can be selected for considering. The sub-GUIs may be activated to create the TSA and VSA systems for observing an electrical network. They create line, node, transformer and generator observers for the TSA system, ZIP load and OXL models, and create line and node observers for the VSA system. They are also able to generate complete TSA and VSA projects for simulations in PSS®NETOMAC. In addition, the evaluation of the unclear network elements could be executed. The OXL functionality can also be tested and the network plausibility can be checked. At the end of the algorithm the power flows of the original network model and the network with ZIP load models are compared to check for possible changes in the new simulation model.

A complex and large network model, which contains many different elements and areas, was used to test the developed concept. For testing purposes, only some areas of this network model were taken. The considered areas contain 96 power plants, which are defined for the simulations as generators, 518 lines, 445 transformers, 1246 bus bars, 498 loads, 247 compensations, different voltage regulators and frequency controllers. This network model has many voltage levels, from high to low voltage (750 kV to 0.4 kV).

This power grid model was chosen because it contains principally all types of electrical elements which can be interesting for dynamic network simulations. In addition, this model has several areas that makes it more complex. Therefore, this power grid model can be used to test all manner of critical situations which can occur in electrical networks.

III. OXL INTEGRATION INTO A POWER GRID

A. Over Excitation Limiter (OXL)

The excitation system of the synchronous generator must deliver the direct current to the rotor field winding. The voltage at the generator connection can be controlled by regulation of the field current and voltage. An automatic voltage regulator (AVR) is one of the control types which regulates the terminal or remote set point voltages [12] [16]. To limit the overvoltage in these systems an Over Excitation Limiter is used in the electrical networks [17].

The OXL modeling is discussed in detail in the literature [18]. Basically, the take-over and the summed type limiters could be utilized in power grids. The summed limiter is able to change the set point of AVR and, therefore, to better use its capability, while the take-over OXL can only roughly limit the voltage [12]. Hence, the summed OXL was chosen within this work and its concept is shown in Figure 3.

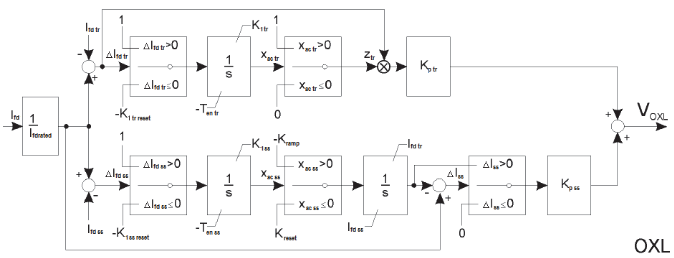

Figure 3. OXL block diagram [12]

The upper part of the block diagram illustrates transient limitation and the lower section the steady state limitation. The transient part allows short-term overloading above current limit $I_{fd\ tr}$ for time $T_{en\ tr}$. After this period the limiter is activated by multiplying the control deviation and gain $K_{P\ tr}$. The steady state part of the block diagram waits 10 seconds ($T_{en\ ss}$) [19]. When there is a positive signal $x_{ac\ ss}$ the second integrator of steady state with the initial $I_{fd\ tr}$ condition is activated and integrated to steady-state limit $I_{fd\ ss}$. K_{ramp} defines ramp inclination, while K_{reset} resets the excitation limit [12].

B. Concept of automatic OXL integration into a power grid

OXL has a major influence on the voltage stability. Therefore, it needs to be included in the VSA. But the OXL model does not belong to the standard models of PSS®NETOMAC. Hence, within this work a concept of automatic OXL integration into a power grid was developed.

First of all, to use the OXL for a considered generator its functionality and compatibility with this generator and its AVR system should be tested in a so-called test electrical network model. Finally, if the OXL is suitable for the considered generator and it is able to limit voltage without making the test network instable, the OXL could be used in the network model of the real power grid. The developed MATLAB routines are able to conduct such OXL functionality test completely automatically.

Usually the electrical network models that are used for the integration with the DSA system are quite large. Therefore, it is not always possible to determine the influence of the regulating elements on a power grid directly in the original model. This influence can be more easily analysed in a small network model.

Hence, within this work such a test network model was developed for testing OXL functionality and its influence on a considered generator with AVR and on a whole power network. Accordingly, for this analysis, a test network must include a generator with a voltage regulator. Therefore, the developed test network model contains two generators (an analysed one and the second with the infinite apparent power), a transformer, which connects the analysed generator with the network model, a small controlled load (P=1MW, Q=1Mvar) and two lines connecting the generators [15]. This test network model is shown in Figure 4.

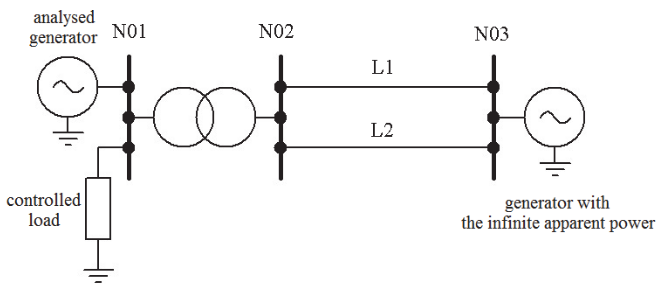

Figure 4. Test network model [15]

To test the OXL that is implemented in the standard voltage regulator the reactive power of the controlled load must be strongly increased, usually to around 80% of the apparent power of the generator. When there is a large increase of reactive power consumption on the bus bar the considered generator must compensate this power. When this occurs, the excitation current increases and exceeds the rated excitation current of the generator. At this moment the OXL is activated for limitation of the excitation current.

C. OXL testing in the developed test network model

To test the MATLAB routines for the OXL functionality analyses another network model of a real power grid was chosen which contains many different standard AVR types. Therefore, it is interesting for testing the concept of automatic OXL integration into a power grid. The network model includes 119 power plants, 527 lines, 210 transformers, 416 bus bars, 299 loads. The network model has many voltage levels between 115 kV and 500 kV.

In addition, a topology of this electrical network was built for the clear graphical representation in PSS®SINCAL [21]. This topology is shown at the Figure 5.

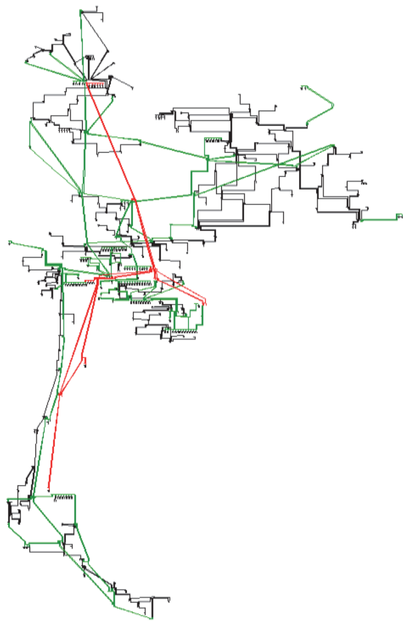

Figure 5. Network model of the real power grid for OXL testing [15]

To test OXL functionality the excitation current of the generator, the bus bar voltage and the voltage change, which occurs because of the OXL, must all be analysed. If the OXL functions properly, it must reduce the generator excitation current to its limit value. At the same time, the OXL must not cause strong oscillations in the network model.

The developed MATLAB routines are able to plot some of the physical magnitudes that are needed to evaluate the OXL functionality for a considered generator. For example, Figure 6 shows the different time curves of a generator with the AVR+OXL system. Figure 6 includes three parts: the first part shows the excitation current of the d-axis of the generator; the second part – the voltage of the generator bus bar; the third part - the voltage which occurs when the OXL is activated.

In the first part of Figure 6 three time curves of the generator excitation current are shown. The red graph is the excitation current of AVR without OXL, the blue one - the excitation current of AVR with OXL, and the black one - the rated excitation current of the synchronous generator. The second part shows two curves: the red one is the voltage on the synchronous generator bus bar without OXL; the blue one - the bus bar voltage of the generator with OXL. The last part shows the OXL voltage which occurs when the OXL is activated.

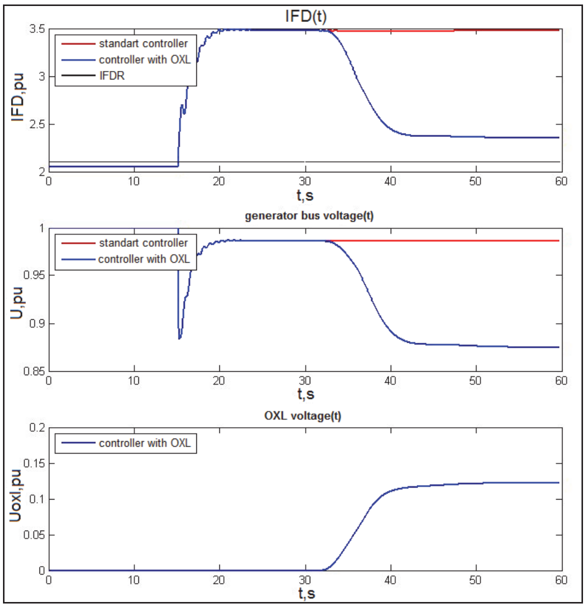

Figure 6. Time curves of x generator with the AVR+OXL system

Hence, this function helps to analyse the OXL functionality and to evaluate the advisability of its use for generators in power grids. In the considered example OXL functions appropriately and limits the excitation current. Therefore, it could be built into the AVR of the considered synchronous generator.

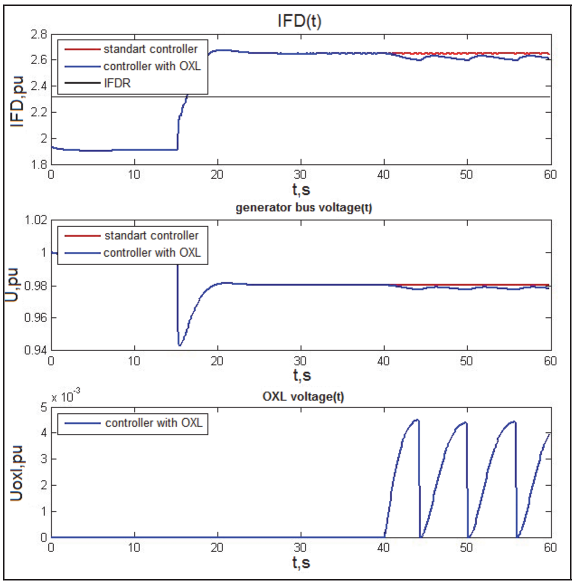

Figure 7. Time curves of y generator with AVR+OXL system

Figure 7 shows the OXL functionality for another generator. As one can see, when the excitation current decreases the OXL no longer functions. The excitation current in this example raises and activates the OXL again. Therefore, the process repeats. Consequently, the oscillations occur in the regulation proses of the synchronous generator and, accordingly, in the magnitudes which are dependent on the OXL.

The OXL must not be used for this generator because it does not improve the functionality of the AVR, but instead it only makes the system instable.

IV. Power Grid Plausibility Check

To improve the reliability of a network model with the DSA system a network model must be checked for its plausibility. This is an important issue because poor modeling or inaccurate snapshot data could lead to power flow inconvergency of the network model or to the load flow which may not be realistic.

A. *Concept of plausibility check*

The developed MATLAB routines are able to analyse the main criteria for the evaluation of the power grid plausibility. Therefore, active and reactive power balances in the system, energy conversion efficiency (η) of generators and loads, bus bar overloading, voltage angle difference of lines, and power balance on the slack node can all be checked. In addition, loads that have duplicate names are also identified.

Finally the original network model and modified network model with ZIP loads are compared and are represented as graphs.

B. *Testing of plausibility check concept*

The MATLAB routines automatically evaluate the plausibility of network elements and generate curves after the load flow simulation which help to assess the network plausibility.

To test this concept the same network model that was used to test the concept of the DSA system integration into a network model was used. First of all, active and reactive power balances of the power grid model were identified (Figure 8). Then, the generators and loads with cos phi less than 0.65 and slack nodes with overloading were displayed. Bus bars with an overloading of more than 10% from the rated voltage and lines with a voltage difference of more than 20° were also shown (Figure 9).

Finally, the power flows of the original network model and the model with a VSA system were analysed. Hence, the active and reactive powers of the generators and loads of both models were compared and displayed (Figure 10). In addition, the voltage difference of generator and load bus bars of both models were shown (Figure 11).

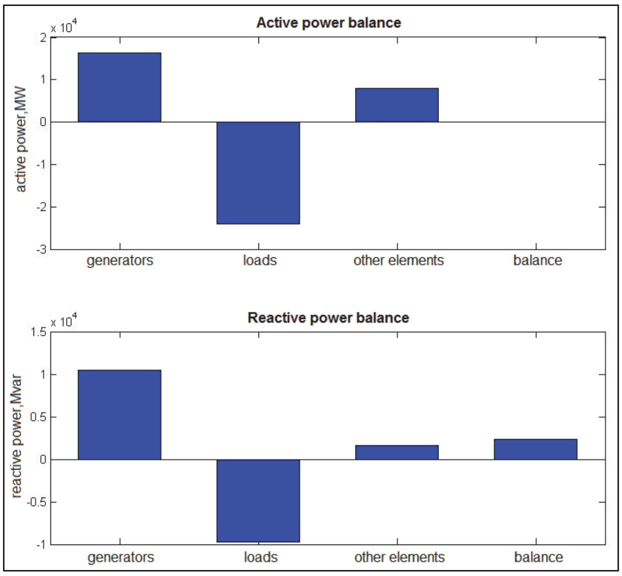

Figure 8. Active and reactive balances in the network model

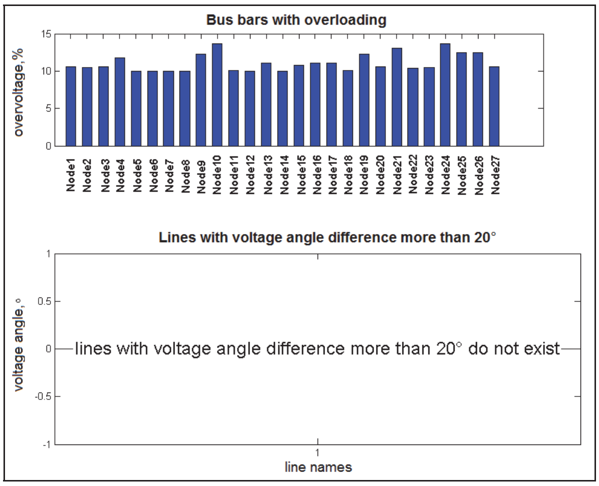

Figure 9. Bus bars with overloading and lines with voltage angle difference more than 20°

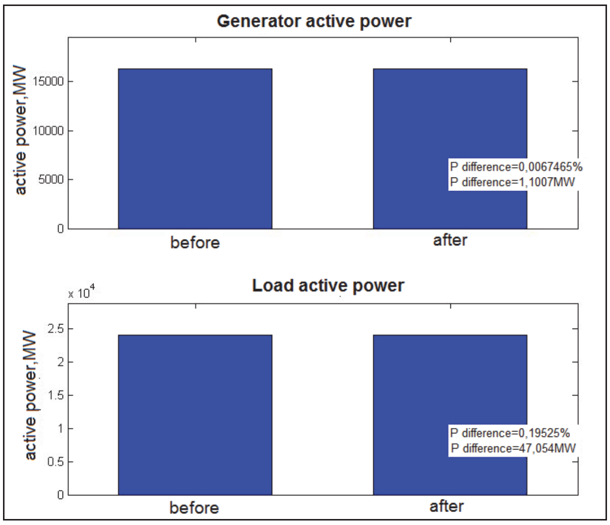

Figure 10. Active power of generators and loads in original and VSA network models

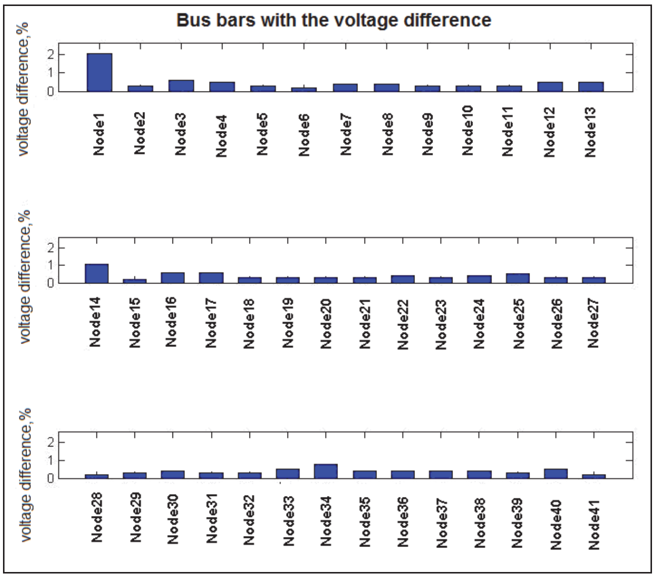

Figure 11. Bus bars with the voltage difference in theoriginal and VSA network models

V. CONCLUTIONS

In this work a new procedure for integration of electrical network simulation models with the DSA system was developed in MATLAB. Therefore, standard DSA index models could be completely automatically integrated into an electrical network model. The test network model and procedure for testing the OXL functionality was also developed. In addition, the method for checking the plausibility of the network power flow was created. Finally, a manual with the necessary steps for using the developed software was written.

The developed procedures for the DSA system and OXL integration and the evaluation of the network plausibility were successfully tested in the different power grid simulation models. Therefore, it was established that the considered large network model with different areas responds to all criteria of stability and plausibility. In addition, the OXL functionality was tested in two standard AVRs of another network model (Figure 5).

The MATLAB prototype that was developed as part of this work was later used in the development of the software SIGUARD® DSA [20] by Siemens AG.

Nevertheless, the procedures in MATLAB could be further developed, e.g. more stability criteria or new DSA indices may be implemented in MATLAB routines in the future. The settings of the OXL could also be improved and changed.

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