Analysis of the Criterion for Connecting New Source to Distribution Grid According to the Steady State Evaluation

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Abstract:
Nowadays power systems, especially the electrical distribution grids are accommodating different renewable technologies resulting into increasing complexities and instabilities. The dynamic growth towards to renewable energy is measured by also considering the impact of distributed generation on the grids. Distributed generation is the electricity production from small sources and is located close to the final consumer. The purpose of distributed generation deployment is to improve the energy independence and if appropriate technology is used, distributed generation can participate on grid control actions. Besides the declared advantages in favor of distributed generation, the responsible bodies have to take measures to ensure the advantages will become visible. The base of safe and sustainable distributed generation deployment is the planning and setting the national targets based on the technical assessment. With planning national aims for renewable energy sources is necessary to regard various technical restrictions. One of the basic criteria for connecting new source to distribution grids is to adhere the voltage limits in networks. In efforts to estimate the impact of operation of a new source on voltage, distribution network operators define a criterion for the maximum permitted voltage change in steady state operation. This article deals with analysis of a voltage criterion and compares it with steady state calculation using the simulation model of 22kV feeder.

Key-Words: simulation model, steady state, swing bus, voltage change, new source, criterion

1 Introduction

Renewable energy sources integration has been extensively increased in the electric power distribution system. To exploit renewable energy sources more effectively, grid connection of renewable energy sources should be done in the way to eliminate negative local impacts on distribution grids [7],[8]. Distributed generation has gained so much attention as the internet and information and communication technologies in the 1990s – it has become the hottest and most discussed topic among global leaders, investors and in mass media [1]. As in [2], distributed generation can be beneficial if it meets at least the basic requirements of the system operating philosophy and feeder design.

National targets give the shares of renewable energy share in total energy consumption and the development of renewable and sustainable energy should reflect the national and technical specifications. The national targets should reflect not only the economical aspects of each country, but it should be based primarily on the technical assessment. The technical assessment should reflect the main pillar of the energy policy, which is the network safety, sustainability and reliability of energy supply. In addition, the targets and the lack of renewable energy sources should comply the requirements for systemic operation at the transmission level as well as the requirements for the local operation at distribution level. (Fig. 1)

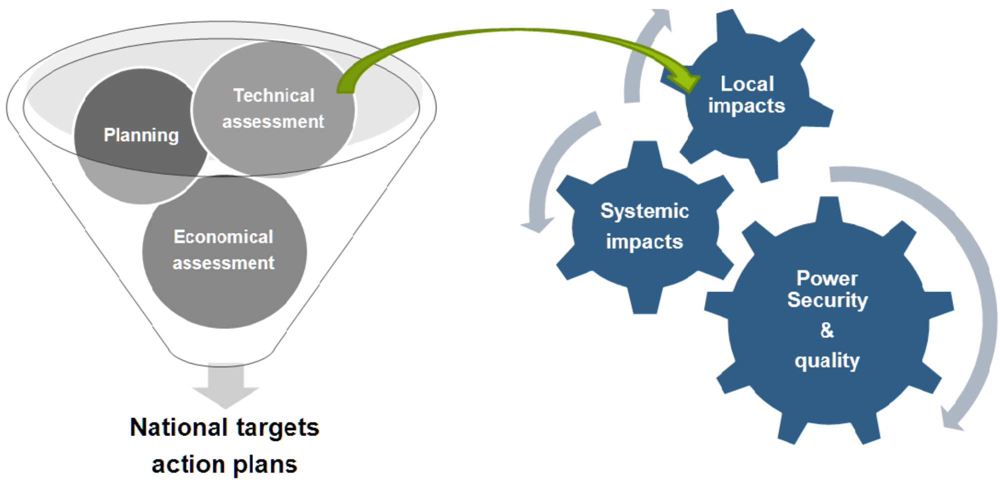

Fig. 1 General approach to set the National targets for renewable energy

When assessing the local impact of new source or impact of the distributed generation, the technical requirements of distribution system operator (DSO) should be considered. DSO play a key role due to the responsibilities for distribution network operation. The DSO is responsible for:

- safe distribution network operation
- development of distribution network and planning the investments to increase the network capability
- power quality in distribution network

The importance of DSO in the area of distributed generation development is underlined, because he is also responsible for the final decision, whether accept or refuse the connection of new small source to the distribution grid. In the process of review of a new small source connection to the network, a distribution system operator and producer are obliged to take measures to prevent inadmissible reverse impacts in connection with power quality.

The distribution system operator specifies technical conditions for connection into the distribution system always considering possibility of deterioration of power quality in the concrete location. Especially the following conditions are concerned: [3], [4], [5].

- electromagnetic compatibility of appliances,
- reverse influence of voltage quality in the distribution system.

The user´s appliances connected to the network are required to resist expected disruptions specified in EN 50 160. In connection with reverse impacts of the sources to the network, distribution system operators exemplify, except for requirements specified in the norm EN 50 160 [6], also other additional criteria for the source connection into the system. In case of the source connection into the MV network, the following criteria are concerned:

- permitted voltage change in steady state,
- permitted voltage change upon switching (fast voltage change),
- flicker,
- emissions of harmonic current.

One of the main above mentioned criteria is the requirement for permitted voltage change in steady state, in other words, the load flow calculation.

2 Definition of the Criterion for Steady State Voltage Change

In modern power system, voltage stability is a major concern. To maintain voltage stability, it is desirable to assess effect of any unforeseen events and identify the nodes which are more sensitive. The most important task for distribution engineer is to efficiently simulate the system so that effective corrective actions can be taken. Load flow analysis is one of the techniques to simulate the system in steady state operation [9].

Steady state represents such a state of the network when no time changes of effective current and voltage values occur. With regard to complexity and extensity of power system it is obvious that in reality such steady state does not occur. It is caused by a floating load caused by customers with their random consumption and fluctuation of production. Various methods are used for calculation of steady state depending on what is known. In case that the task is mathematically linear, the suitable method is Gaussian elimination.

Especially iterative methods are used in practice because powers are mostly entered in the network nodes. Out of them, especially Gaussian, Gauss-Seidel and Newton iterative methods are used most frequently. In all the cases it is necessary to determine at least one so-called "Swing bus". Swing bus represents location in the network where the network voltage is kept with required intensity and phase. Despite the fact that swing bus is a purely mathematical concept, in practice it is possible to interpret it as a location of the system with a great hardness (with a great short-circuit power) and constant voltage. This implies that this feature is represented best by locations in the transmission system or on the interface of the transmission and distribution system. Voltage change in steady state in location of the source connection is caused by voltage drop on a power line induced by current traverse (by voltage change) after connection of the source. We will use a simplified case according to Fig. 2 for derivation of the relation for calculation of voltage change in steady state.

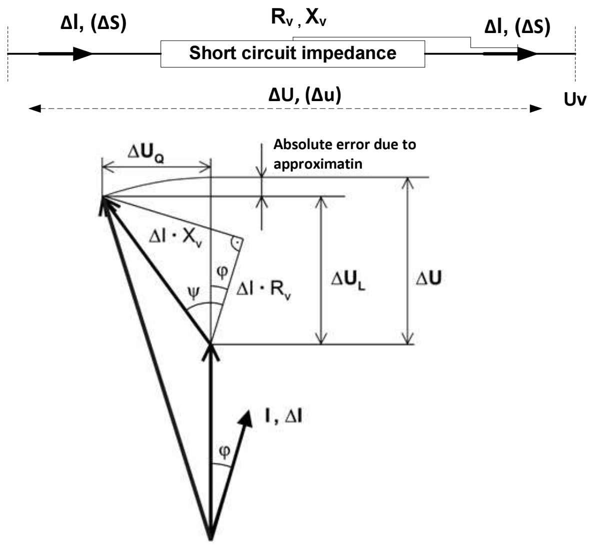

Fig. 2 Cross and longitudinal voltage change

Approximate calculation for voltage change should be figured out as follows:

$$\Delta U \approx \Delta U_L = \Delta I\left(R_V \cos\psi_{kV} + X_v \sin\psi_{kV}\right) \tag{1}$$

$$\Delta U \approx \Delta U_L = \frac{\Delta P}{U_V} R_V + \frac{\Delta Q}{U_V} X_V \tag{2}$$

$$\Delta u = \frac{\Delta U}{U_V} \approx \frac{\Delta P}{U_V^{\,2}} R_V + \frac{\Delta Q}{U_V^{\,2}} X_V \tag{3}$$

$$\Delta u = \frac{\Delta P}{S_{kV}} \cos\psi_{kV} + \frac{\Delta Q}{S_{kV}} \sin\psi_{kV} \tag{4}$$

$$\Delta u = \frac{\Delta S}{S_{kV}}\left(\cos\psi_{kV}\cos\varphi + \sin\psi_{kV}\sin\varphi\right) \tag{5}$$

$$\Delta u = \frac{\Delta S}{S_{kV}} \cos\left(\psi_{kV} - \varphi\right) \tag{6}$$

where
U_V - conjugated voltage in the connecting point
ΔS - apparent power change
S_{kV} - short- circuit power in the connecting point
Ψ_{kv} - short-circuit impedance angle in location of the source connection
φ - production power factor
ΔP - active power change
ΔQ - reactive power change
X_V - network reactance in the connecting point
Rv - network resistance in the connecting point

Voltage increase Δu induced by operations of connected sources must not, in the most unfavourable case (in the connecting point), exceed 2 % for connection of a source with the connecting point in the 22kV and 110kV networks in comparison with voltage without their connection.

$$\Delta u_{vn} \leq 2\% \tag{7}$$

The maximum source power (S_{Amax}) in MV network may be derived using the following relation (6) from the above mentioned definition of maximum permitted voltage change in steady state:

$$S_{Amax} \leq \frac{2\% S_{kV}}{\left|\cos\left(\psi_{kV} - \varphi\right)\right|} = \frac{S_{kV}}{50\left|\cos\left(\psi_{kV} - \varphi\right)\right|} \tag{8}$$

where
φ- phase angle between current and voltage of a source upon maximum apparent power S_{Amax}

If source power S_{Amax} is known in advance, then voltage increase in the connecting point shall be calculated according to the relation:

$$\Delta u = \frac{S_{A\max}\cos\left(\psi_{kV} - \varphi\right)}{S_{kV}} \tag{9}$$

In the interconnected networks, 110 kV networks and/or upon operation of several dispersed sources in the network it is necessary to determine voltage increase by means of a complex operation of the network. At the same time requirement for Δu in the most unfavourable connecting point must be met. The relation (9) does not contain information about swing bus. Upon complex calculation of steady state of the system it is necessary to define at least one node as balance – swing bus. Such a node performs as an ideal voltage supply towards the rest of the system, the choice of its location affects the final solution of steady state calculation

3 Analysis of the Criterion for Steady State Voltage Change using the simplified model of HV feeder

Derivation of the relation according to 5) implies that analytical calculation according to the relation (9) is not a calculation of steady state. The relation (6) for voltage change within the calculation of steady state expresses voltage change of only that part of impedance which is located between swing bus and location of the source connection. This implies that swing bus location affects result of the calculation within determination of voltage change.

Upon analysis, a simplified network model was used (Fig. 3). Simulation model consists of a simplified 22kV feeder created by a overhead line (type of line ACSR6 95/7) of three different lengths 1km, 30km and 60km, 110kV network equivalent with a respective short-circuit power, transformer and reviewed source. The source is connected at the end of the 22kV feeder, so all the short circuit power at the source connection point is limited by the impedance of 110kV network equivalent, impedance of transformer and the impedance of 22kV overhead line. Transformer impedance was not changed and within every change of swing bus location it was constant, equal to Z_{Tr} impedance.

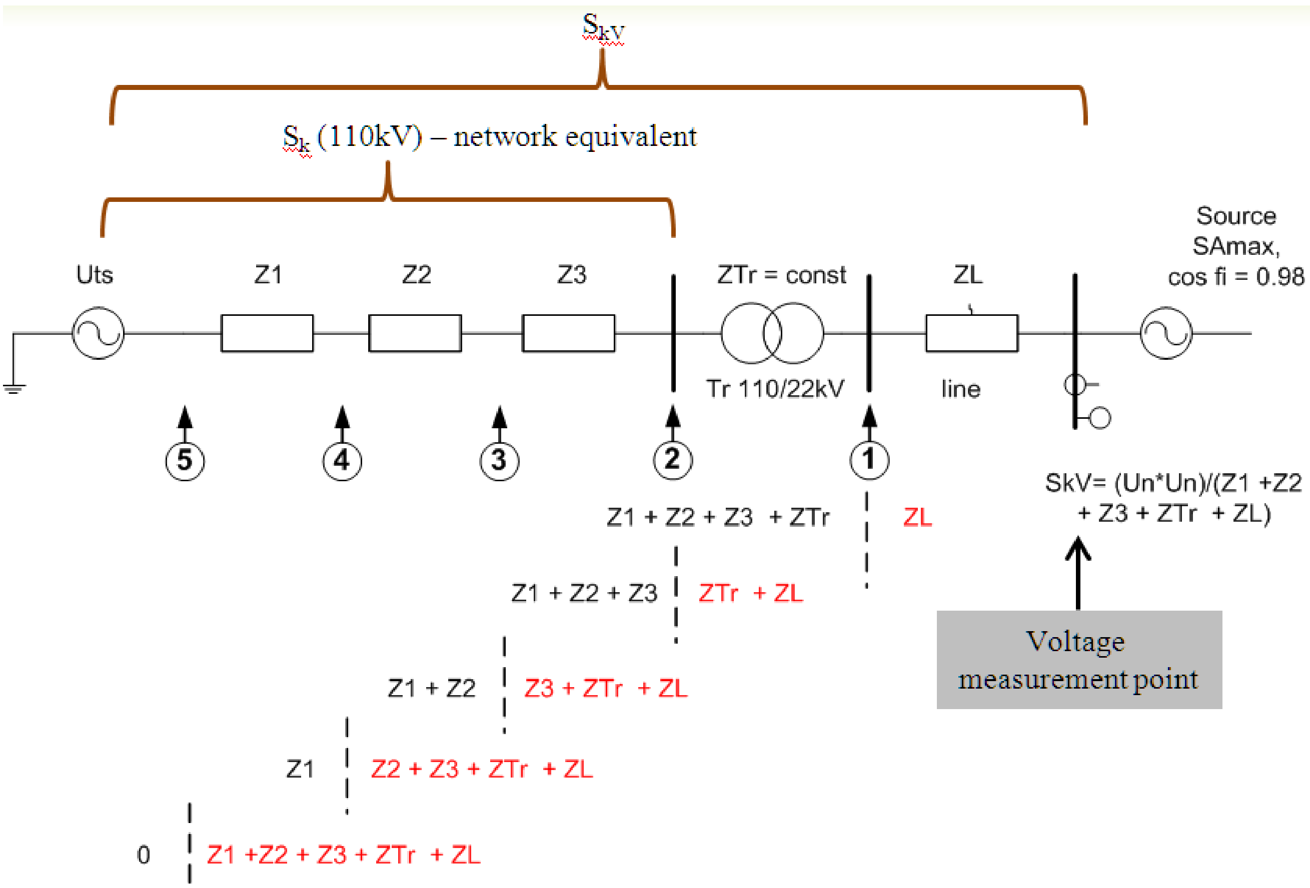

Fig. 3 Simplified simulation model of HV/MV feeder

Nominal power of the source (S_{Amax}) was calculated using the formula (8) and connected at the end of the 22kV feeder. The short circuit power of 110kV network equivalent model (S_k) was set to the value of 191MVA, X/R=7. The overall short circuit impedance was divided to the three equal impedances marked as Z1,Z2, Z3. The swing bus position in the model was changing from the position 1 to the position 5. In other words, the swing bus was replaced in the 110kV network equivalent after each load flow calculation. In the first calculation, the swing bus was placed near to the 22kV feeder, at the high voltage site of transformer and the last position of swing bus in model was far from the transformer. The short circuit impedance in the source connection point (Z_{kV}) is not affected by the swing bus location, but it changes according to the 22kV line length (Z_L) and thus the short circuit power in source connection point (S_{kV}) varies for each line length. The calculated source power is different for each line length, for 1 km line length is equal to 6.59MVA, for 30 km line si equal to 0.82MVA and the source power for the 60km line length is equal to the value of 0.43MVA. The following Tab. 1 shows the steady state voltage changes for each line length, measured at the source connection point, according to the swing bus location in 110kV network equivalent model. The table shows the impedance 1, which is the impedance between the swing bus and 110kV source and Impedance 2 as the impedance swing bus and source connection point at the end of the feeder.

Tab. 1 Simulation results of voltage change according to the swing bus position

	Swing bus loaction	Impedance 1 [Ω]	Impedance 2 [Ω]	Δu [%]
Line length 1km SAmax =6.59MVA	1	$Z1+Z2+Z3+Z_{Tr}$	Z_L	0.47
	2	Z1+Z2+Z3	$Z_{Tr}+Z_L$	0.81
	3	Z1+Z2	$Z3+Z_{Tr}+Z_L$	1.17
	4	Z1	$Z2+Z3+Z_{Tr}+Z_L$	1.51
	5	0	$Z1+Z2+Z3+Z_{Tr}+Z_L$	1.93
Line length 30km SAmax =0.82MVA	Swing bus location	Impedance 1 [Ω]	Impedance 2 [Ω]	Δu [%]
	1	$Z1+Z2+Z3+Z_{Tr}$	Z_L	1.77
	2	Z1+Z2+Z3	$Z_{Tr}+Z_L$	1.81
	3	Z1+Z2	$Z3+Z_{Tr}+Z_L$	1.85
	4	Z1	$Z2+Z3+Z_{Tr}+Z_L$	1.9
	5	0	$Z1+Z2+Z3+Z_{Tr}+Z_L$	1.94
Line length 60km SAmax =0.43MVA	Swing bus location	Impedance 1 [Ω]	Impedance 2 [Ω]	Δu [%]
	1	$Z1+Z2+Z3+Z_{Tr}$	Z_L	1.94
	2	Z1+Z2+Z3	$Z_{Tr}+Z_L$	1.97
	3	Z1+Z2	$Z3+Z_{Tr}+Z_L$	1.99
	4	Z1	$Z2+Z3+Z_{Tr}+Z_L$	2
	5	0	$Z1+Z2+Z3+Z_{Tr}+Z_L$	2

The graphical interpretation of voltage changes given from the simulations on the simplified model are displayed on the following Fig. 4

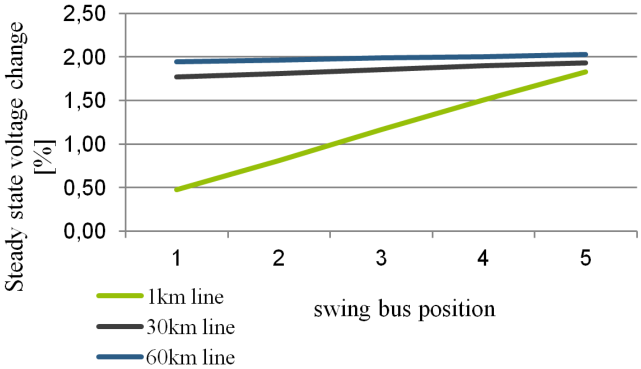

Fig. 4 Dependence of voltage changes on swing bus location

From the simulation of steady state voltages results, that by assessing the local impacts of the source on voltage changes in steady state is important, how the network is modeled. In case of the assessment of the source operating near to the HV/MV transformer, the voltage change is depended on the model of 110kV network equivalent and the swing bus location. If the source is assumed to be operated at the end of the long MV, the swing bus location in HV network doesn't affect the results. As in [] this is important to note, if planning the targets for distributed generation based on modeling power networks and simulations from the technical point of view.

3.1 Estimation of voltage changes considering the change of short circuit power of network equivalent model

In the previous section, we assumed one constant value of short circuit power of 110kV network equivalent model. In real networks, the value of short circuit powers of 110kV network varies between 191MVA to 1910MVA. In this section we will investigate the steady state voltage changes considering also the different values of network equivalent model. Within this simulations, the value of short-circuit current of the 110kV network equivalent ranged from 1kA – 10kA (191MVA-1910MVA). The change of short circuit power of the 110kV network was achieved by changing its impedance (Z1+Z2+Z3). The ratio X/R of 110kV network equivalent ranged from 3 to 7 (from 70° to 82°). In this case the length of the line was constant, equal to the length of 1km. Upon this simulation, short-circuit power in location of the source connection (at the end of the 22kV line) was calculated for each combination of short-circuit power of network equivalent. Based on the relation (8), maximum source power S_{Amax} (with neutral power factor cosφ=1) was calculated for each of the combinations the way that the change of voltage in steady state after connection equals 2 %. Consequently, steady state with various swing bus locations was calculated for each source power calculated this way. Swing bus location is depicted on Fig. 3 by numbers 1-5. The result of calculations is the change of voltage in location of the source connection as dependence on swing bus location in the network model. The following Fig. 5 depicts dependence of voltage change in location of source connection on short-circuit current of 110kV network equivalent and swing bus location.

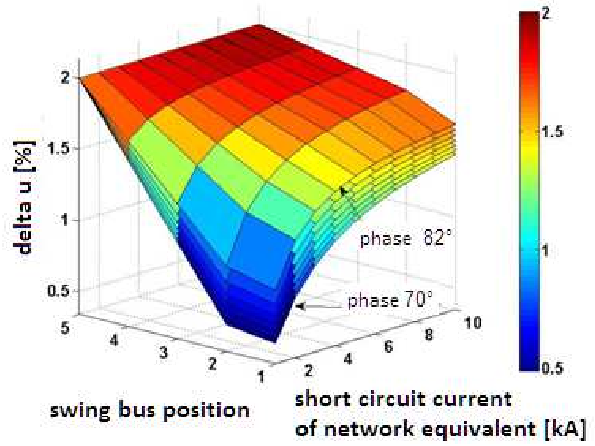

Fig. 5 Dependence of voltage changes on swing bus location and short-circuit current of 110kV equivalent source with 1km line length

The course of voltage change shows that in all the cases when swing bus was located in front of all the short-circuit impedance of 110kV network equivalent , i.e. location No. 5, voltage change in steady state equals permitted value 2 %. Change of voltage in location of the source connection decreases by change of swing bus location closer to the transformer, i.e. source power S_{Amax} is not sufficient enough to cause 2% voltage change. Dependence of voltage change also implies that with small short-circuit powers of network equivalent the impact of swing bus location is more obvious than with higher short-circuit powers.

In the next simulation, we extended the simulations, considering also the change of 22kV line length. Finaly this simulations includes all the combinations of short circuit power of 110kV network and line length. The line length varies from 1km to 20km. The next Fig. 6 displays the simulation results of voltage changes at the end of the feeder.

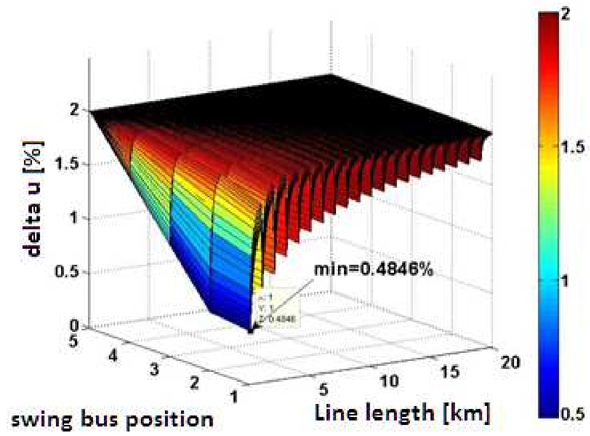

Fig. 6 Dependence of voltage changes on swing bus location and short-circuit current of 110kV equivalent source with line length 1km-20km.

4 Analysis of the Criterion for Steady State Voltage Change using the complex model of 22kV network

In the previous section, we used the simplified model of 22kV network to investigate the operation of electrical source connected at the end of the feeder in steady state. We have note, that in some of the cases, the voltage change didn't reach the permited value 2%, even though we used the equation (8) to calculate the maximum source power. In this section, we used the model of real 22kV network to simulate the impact of swing bus position on steady state calculation. The model is based on real data of the network. It consist of one HV/MV transformer, 14 feeders an many of the different P,Q loads. The sources (source S1 and source S2) was placed in two nodes in one feeder. Source S1 operates near to the transformer, and the Source S2 operates at the end of the feeder. The nominal power of this source was calculated using the equation (8). The next Fig. 7 shows the model of 22kV network. For this purpose only the one feeder with sources is pictured in detail.

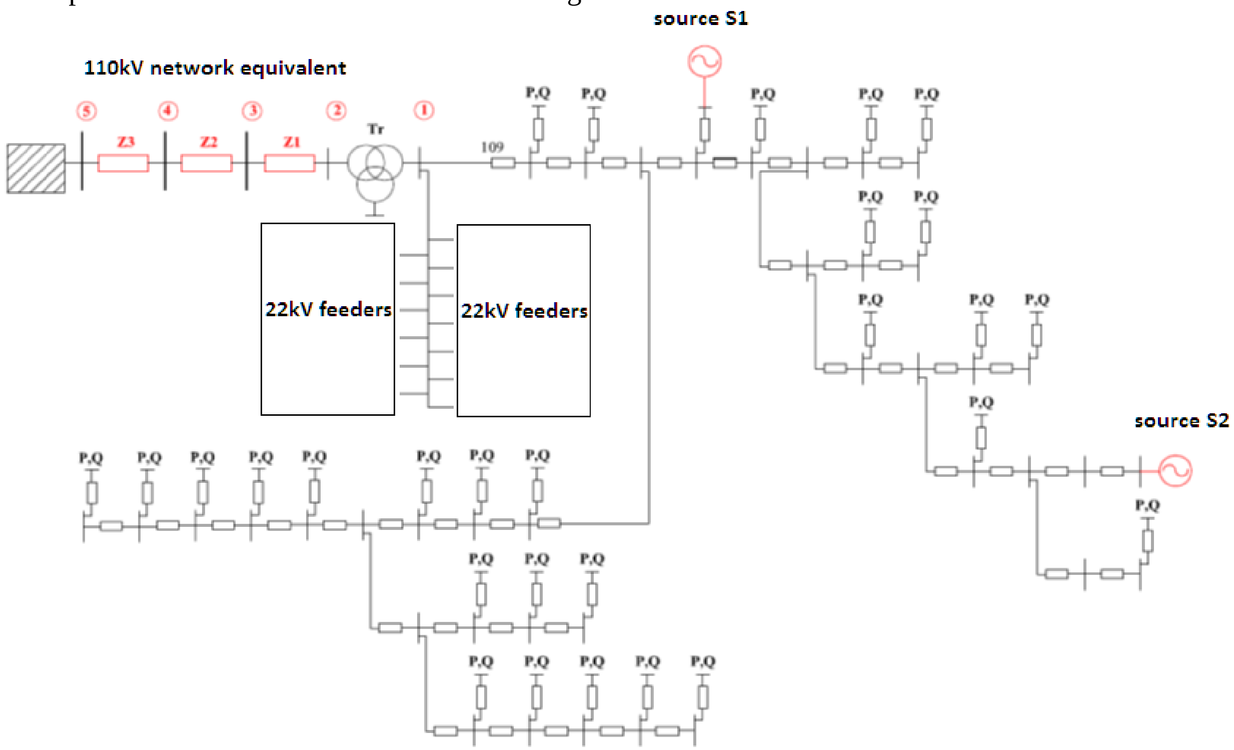

Fig. 7 Model of real 22kV network

The Fig. 8 displays the simulation results of steady state calculations and voltage changes caused by source operation.

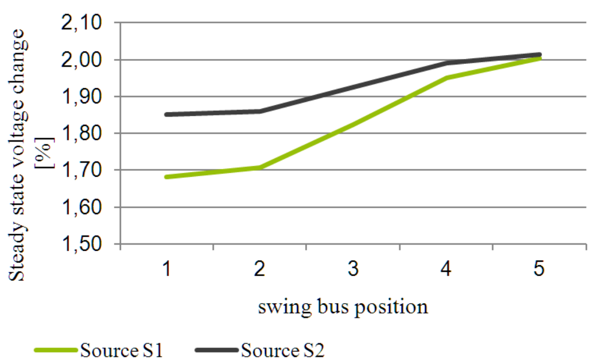

Fig. 8 Simulation results of source operation in 22kV network

The voltage curves obtained from the simulation on 22kV model confirm the impact of swing bus location in steady state calculation. As well as in simplified model, the influence voltage change caused by source operation depends on swing bus location and the source operation point.

5 Conclusion

The analysis and simulations proved that swing bus location in the model for calculation of steady state (load flow) considerably affects the steady state calculation and thus it affects the final assessment of new source connection to the network and its impact on voltage changes. If the assessment of the source connection using the simulation model is required is required and swing bus is located close to the HV/MV transformer, then the source review from the view of permitted voltage change is optimistic, i.e. the review will imply that the source may have a higher installed power as if swing bus was located further in the HV network.
Because of increase of distributed generation, the use of simple empiric relations for calculations of voltage change is insufficient. Using the empiric relations given by distribution system operator is simple but its accuracy is not satisfactory with regard to complexity, reciprocal influence of the sources and loads. The use of a simulation model for analysis of steady states after connecting a source is more suitable and precise especially in case of more complex networks. When creating the simulation model, in order to achieve more precise results, it is therefore necessary to model also a part of 110kV

system and to locate swing bus as far from the HV/MV transformer as possible towards the transmission system where the system is electrically hard. This paper pointed out the importance of the right approach to build the simulation model, considering the influence of swing bus location on steady state calculation. This attention to the modeling of electrical networks became more actual and important with the development of distributed generation and planning the national targets for renewable energy from the technical point of view.

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