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Report on saving potentials in energy transmission and distribution

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Cover Photo: *electricity transmission tower.*

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Table of content

1. Introduction

Electricity plays a significant role in the final energy consumption. In EU-27 in 2010 the total energy consumption by end users was 2837 TWh where electricity as a final energy product contributed with 21% in all energy sector (Eurostat, 2012).

The electricity generator depending on the primary energy source can be located close to the consumer (in distribution grids) or far away from the main consumer. For example, biomass-waste power plants and photovoltaic (PV) systems usually characterise with small capacity and they are installed locally in distribution grids, where the main part of their generated power is consumed locally. While wind farms, huge hydro and fossil power plants are characterized with bigger capacities and they normally are displaced close to the energy source, e.g. fossil fuel plants close to the main fuel supply ways. Thus the transmission lines are necessary for efficient electricity delivery.

The amount of the delivered electricity is dependent not only on the demand but also on the energy losses in electricity delivery process, which includes losses in both transmission and distribution lines. These losses can comprise one tenth from the gross electricity generated. Increasing of distributed RES capacity, electricity grid upgrades and extensions could lead to the decrease of the relative energy losses in grid in long term planning (Purvins et al., 2011).

The aim of the study is to analyze technically the energy saving potentials in electricity grids including both transmission and distribution parts. Obviously, placing generators closer to demand points decreases the necessary conductor length, which furthermore reduces the reactive power consumption in conventional AC lines due to their impedance (or generation in AC cables due to their capacitance) leading to lower losses. However, the majority of power generators are not flexible regarding the installation place and they are installed close to the primary energy source (e.g. coal power plants close to the coal mines or to the main coal supply ways, wind farms in windy regions). Some generation technologies have fewer constraints on siting: gas powered plants due to developed gas network. Knowing that, the focus is on technical active loss reduction in electricity grid through different sitings of flexible power generators (like gas turbines).

2. Insight in theoretical bases of active losses in electricity grid

The difference of the active power transmitted to the active power delivered through a conductor suggests the active losses. The energy received will be always lower then the sent energy because of the conductor's properties. These thermal losses of energy transfer through electricity grid depend on the resistance of the conductor (line/cable):

$$P_{loss} = P_S - P_R = R * I^2, \qquad (1)$$

where P_S is the active power sent, P_R is the active power received, R is the line resistance and I the current flowing through the conductor.

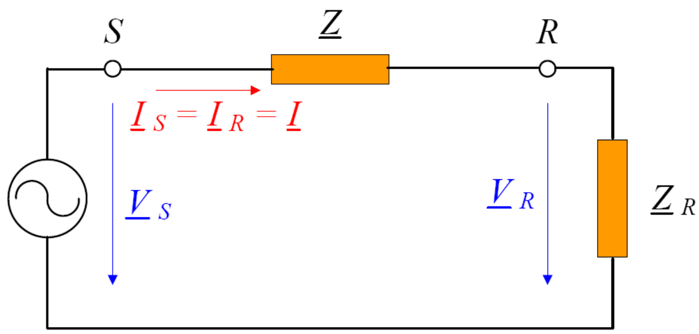

Fig. 1 Simplified equivalent circuit of conductor

The resistance is a firm parameter of the conductor and depends a little bit on the conductor temperature; however, for the shake of simplification this temperature influence is usually ignored in electricity grid studies. Whereas the current is variable and its value is influenced by the voltage and the load of the receiver, the energy amount to be transferred. The magnitute of the current can be calculated as follows:

$$\mathrm{I} = \frac{\mathrm{V_S}}{\mathrm{Z} + \mathrm{Z_R}} = \frac{\mathrm{V_R}}{\mathrm{Z_R}} = \frac{\sqrt{\mathrm{P_R^2} + \mathrm{Q_R^2}}}{\mathrm{V_R}}, \qquad (2)$$

where V_S and V_R are the voltages in the sending and receiving point of the conductor, Z and Z_R are the reactance of the line and load respectively and P_R and Q_R are the reactance, the active and reactive power at the receiving end of the conductor.

3. Theoretical reduction of grid losses

From equations (1) and (2) it can be concluded that active losses in a conductor can be decreased by decreasing the resistance, the inductance of the line and the reactive power flow along the conductor (due to the line and the load reactance).

Active resistance is inversely proportional to the cross section of the conductor. This means that increasing the diameter of the conductor its active resistance decreases. However, such solution in increasing the energy transfer efficiency is not feasible, since it increases the capital conductor installation costs and decreases the capacity factor of the conductor. In other words, part of the installed inductor's capacity will be never used. Another way how to decrease the resistance is applying new materials and technologies, like superconductors and gas-insulated lines. These are state of the art technologies but their analysis is beyond of the study's objective.

Reactive power presence in electricity transfer processes is managed to be as small as possible. However, reactive power is needed to meet reactive power demand. The latter mainly refers to the voltage regulation in the grid. Reactive power in the conductor can be decreased applying reactive power compensators like flexible alternating current transmission systems (FACTS). Reduced reactive power flow increases not only electricity transferring efficiency but also the maximum active power transferring capacity.

Furthermore, voltage level plays significant role in electricity transfer efficiency. A number of lines around the world are designed for extra high voltage (1000 kV and more); however, part of them operates at lower voltage because of insufficient demand.

The potential in reduction of electricity transferring losses using FACTS and extra high voltage lines is practically exhausted and balanced between efficient energy transfer and electricity system feasibility. Therefore, no radical changes in electricity transferring efficiency are expected from these technologies.

However, formula (2) shows another parameter, the active power, which reduction will lead to decrease of power losses. It is obviously that by decreasing the portion of the energy to be transmitted the absolute value of losses decreases. That can be achieved through distributed generation bringing generators closer to demand where possible. Thus part of the demand can be satisfied locally.

$$P_R' = P_R - P_{DG}, \qquad (3)$$

In such a way the energy amount to be transmitted is reduced and some portion of energy is generated and consumed locally: (P_{DG}). These generators could be mainly photovoltaic technologies and biomass power plants.

Another way to decrease the active power transferred is optimal siting of power generators on transmission grid level. Stochastically variable power from wind farms requires power balancing in electricity system. It could be realized with flexible generators like gas fueled power plants which collocation in the grid (if possible) will influence the power flows and so the losses.

According to the EU energy projections (Beurskens, 2011) the photovoltaic technologies will generate 83 TWh in EU-27 in 2020. This amount is roughly 2% from the total gross final electricity consumption (3536 TWh). These photovoltaic systems will mainly supply domestic loads providing minor decrease in power flows in the electricity grid in general. Besides wind power will provide 495 TWh electricity (14% of the total electricity consumption).

Knowing the trends on the high wind power contribution in the future electricity generation, the focus in our study is on the optimal siting of flexible generators (like gas turbines) in electricity system. This study is performed through sensitivity analyses on transmission grid level and focuses on the active electricity transmission losses.

4. Reduction of losses in a meshed grid

The reduction of losses in a meshed grid is realized through different siting of flexible generators. These flexible generators will provide controllable and variable power for compensation of stochastically variable and uncontrollable wind farm generation. Such flexible generators could be natural gas fueled plants.

a. Grid configuration

For the electricity network, as a literature search indicates no typical grid scheme seems to be in use for theoretical studies. Therefore, the investigation starts with the simplest meshed electricity network. We assume a conceptual 3-node scheme as the simplest portion of a meshed electricity network (Fig. 2) allowing us to model the response of the electricity network and to evaluate the grid behavior under various scenarios.

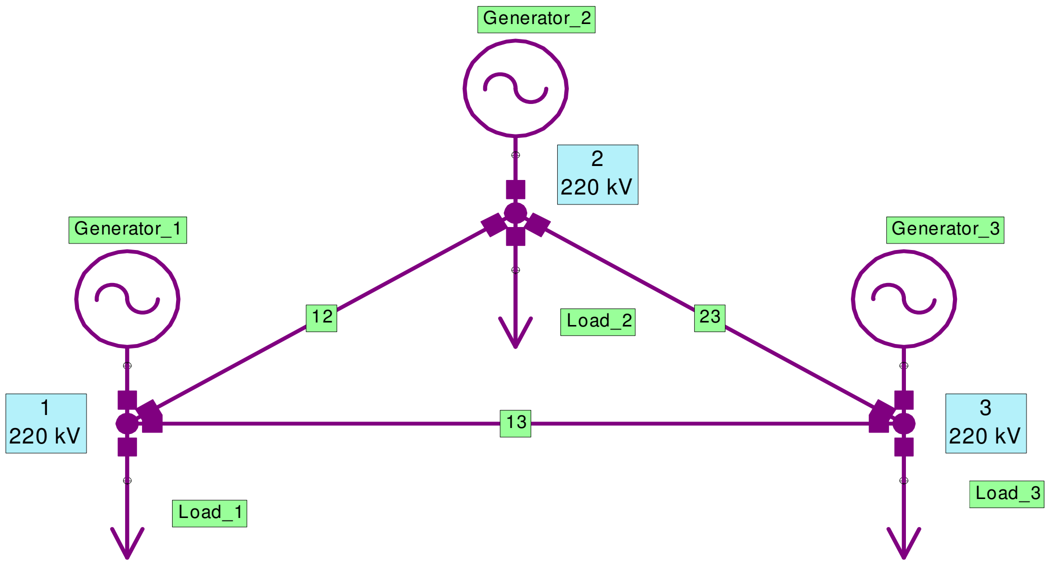

Fig. 2 Simplified meshed grid

Represented in Fig. 2, the triangular shape grid configuration contains three nodes connected through three lines each with other. Every node is therefore connected directly with the two other nodes through different lines.

For the sake of simplicity, an equilateral configuration is assumed. At each of the three nodes different portions of base generators (like coal, nuclear or biomass) and loads are applied as presented in Table 1. It is assumed that the biggest size base generator is collocated at node #1 which is far from the main loads (at nodes #2 and #3). This could represent a situation where coal power plant is located far from the main consumer, e.g. a city. Wind farm is also considered to be located far from the main demand and is connected to node #2. It is expected that the base generation, wind farm and loads are not flexible regarding their topology. However the flexible generation needed for damping the wind farm power variations is assumed having flexibility in its collocation. So, depending on the scenarios the installed capacity of the flexible generators varies from 0 to 250 MW in node #2. Flexible generator in node #3 generates always the amount of power needed for power balance in the system. Is there any wind curtailment?

Table 1 Generation capacities and load

Node	**1**	**2**	**3**
Base load generator, MW	150	50	50
Wind farm, MW	0	300	0
Flexible generator, MW	0	0-250	Power balance
Maximum demand, MW	100	300	500

b. Renewable energy sources

As the contribution of solar energy is considerably minor as compared to wind in transmission grid, it is assumed that in the scenarios wind power plants are the only contributor from variable RES. Nevertheless, in case that there are photovoltaics in the system these would be placed near the demand (e.g rooftops PVs) and for the subject system level this can be seen as a decrease in the demand in the nodes. The total generation capacity in the network under study is assumed to be 900MW, with approximately 300 MW of wind power (for the RES target to be met). Since wind is a variable and undispatchable energy source, it is assumed to be coupled with electricity flexibly produced by natural gas generators.

c. Methodology

The methodology consists of modeling a conceptual electricity network, executing simulations under different scenarios and analyzing the results in view of making indications and recommendations. The output values to be estimated are the losses in the electricity system. Electricity system contains two variable parties: wind farm and demand. Power distribution functions of these two are represented further in this subsection. So, in order to obtain reliable results each scenario should be run several hundred times.

The electrical power flow analysis tool adopted for the simulation is NEPLAN, which performs a steady-state analysis of the transmission network through the 'Extended Newton Raphson' calculation method. Generation (only active power) and demand (both active and reactive powers) in transmission grid nodes are set manually. These generation and demand values depend on the studied scenarios. In addition, flexible generator in the node #3 is modelled as a slack generator. This element consumes or generates as much active power as necessary in order to keep the generation and the demand in the electricity system balanced. The active power of this slack generator is managed by the modelling tool and it represents the power needed for power balance in the system. Furthermore, for all the generators (including the slack generators) the tool manages the reactive power compensation in order to meet the demand in the system and to keep the voltage in its rated value in the nodes where these generators are connected.

i. Grid capacity

220 kV line with single aluminum steal-reinforced conductor and maximum current of 680 A is considered for the study to connect all three nodes. Consequently, the capacity of such line is 259 MVA. The line parameters are as follows: resistance 0.16 Ω/km, reactance 0.64 Ω/km and capacitance 5.75 nF/km (Oswald, 2005). The distance among the nodes and so the line branches are assume to be 100 km amounting the total length of the grid 300 km.

ii. Wind farm data acquisition

For study purposes, wind data was obtained from the joint Reanalysis project (Kalnay et al., 1996) for a representative point in an area of wind farm development close to eastern coast of the UK (Latitude 54.285, Longitude 0). These data contain wind speed values at six-hour (6-h) intervals at the altitude of 10 m. The location of the data point was considered due to the relatively high wind power potential in the North Sea.

Wind speed is estimated at the presumed height of 100m for new off-shore wind turbines. A logarithmic extrapolation of wind speed and tower height (Gipe P., 2004) is used as provided in Equation 1:

$$V = \frac{V_0 \cdot \ln(H / k)}{\ln(H_0 / k)} \qquad (4)$$

Where:

V is (unknown) wind speed at the height H (100 m);

V_0 is (known) wind speed at the height H_0 (10 m);

k is a roughness length constant equal to 0.0002 for water surface.

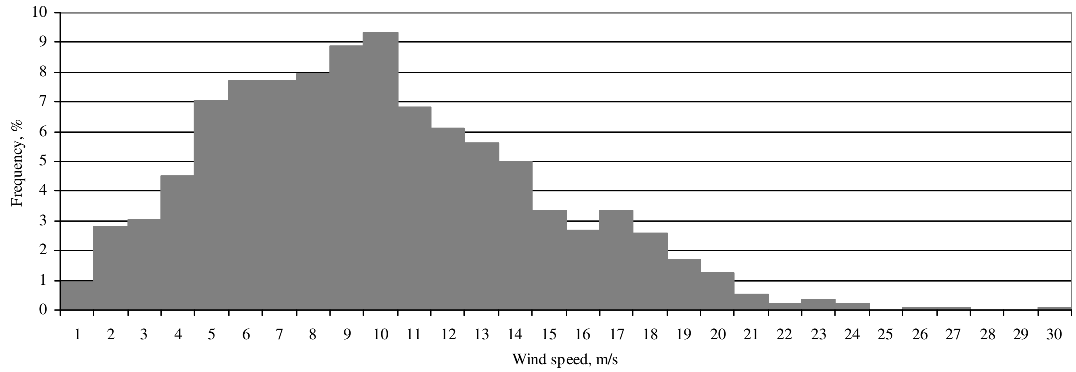

Fig. 3 Wind speed distribution on the node #2

The power output from an entire wind farm takes on characteristics beyond the performance of the individual turbines. Wind farm power production can be calculated with the aid of TradeWind regional offshore equivalent power curve projection (McLean, 2008). These projections include several functions that tend to reduce the wind farm power output, such as the array efficiency (due to wakes of upstream wind turbines), high wind speed cut out, regional topography, spatial averaging, availability, and electrical losses. According to this projection shown in Fig. 4, the ratio of generated power to the rated power is presented as a function of off-shore wind speed. In this curve, the generation never reaches 100% of the rated power. The maximum generation is approximately 90% for a 15 m/s wind speed. Beyond 15 m/s, the wind farm output is capped at 90% until reaching ~24 m/s where the generation suddenly begins to drop. This decline continues for wind speeds of ~31 m/s, where the output from the wind turbine drops and remains to zero.

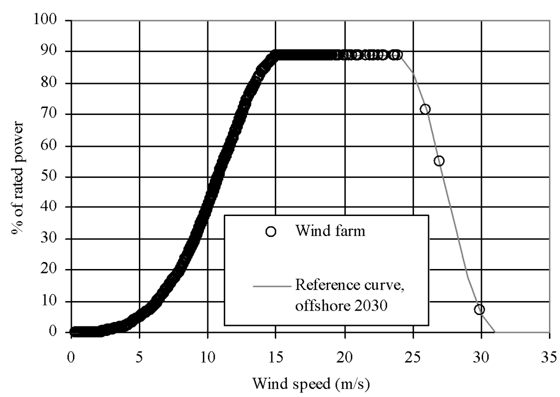

Fig. 4 Wind farm power production projection (Mclean, 2008)

By combining the wind speed data with the power production projection, an estimate of wind power generation at the off-shore data point could be generated. The rated power of the wind farm is 300MW; nevertheless the maximum effective power is 270MW according to the power projection curve. Representative outputs from the hypothetical wind farm are provided in Fig. 5 and they are taken as input data in power simulation. The annual capacity factor is as high as 37.5%.

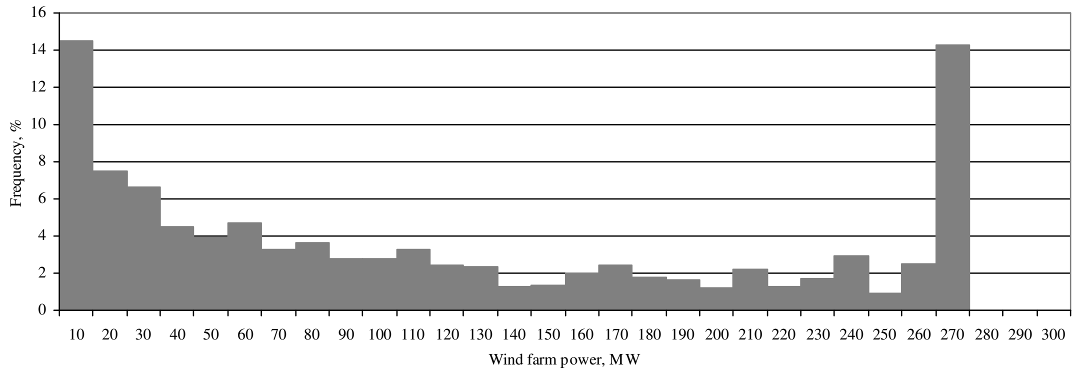

Fig. 5 Histogram of wind farm power output

From the Fig. 5 it can be noticed that the maximum wind farm output (between 260-270 MW) has relatively high occurrence probability (around 14%). This means that there is a high possibility for two critical situations in the electricity system: low and high wind farm output.

iii. Demand curve

Statistical active demand data from ENTSO-E (2012) for the UK in 2010 are used for the study. In this data each month has a different hourly profile as measured on the 3rd Wednesday of each month. We use an annual average from these profiles represented in Fig. 6.

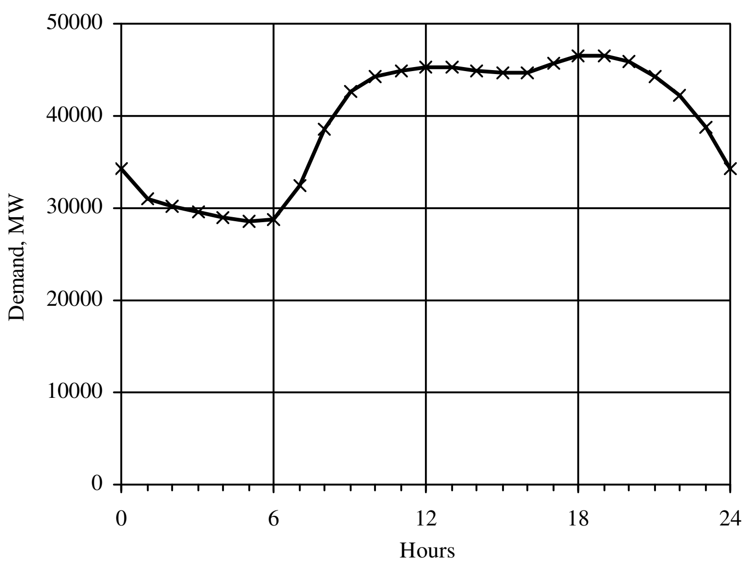

Fig. 6 Representative daily demand profiles in the UK for 2010

This demand profile is applied in each of the three nodes in such a way that the curve does not loose its shape; in other words, the ratio of the peak-to-peak variations to the maximum demand is the same as it is in the statistical demand profiles. The maximum demand is taken as a base value. The demand distribution profile in per unit values is presented in Fig. 7. The peak demand is considered to be the base value. The demand distribution shows that the critical conditions of maximum or minimum demand are dominant and occur in 88% of the time in daily profile. The power factor of the load is assumed to be 0.7.

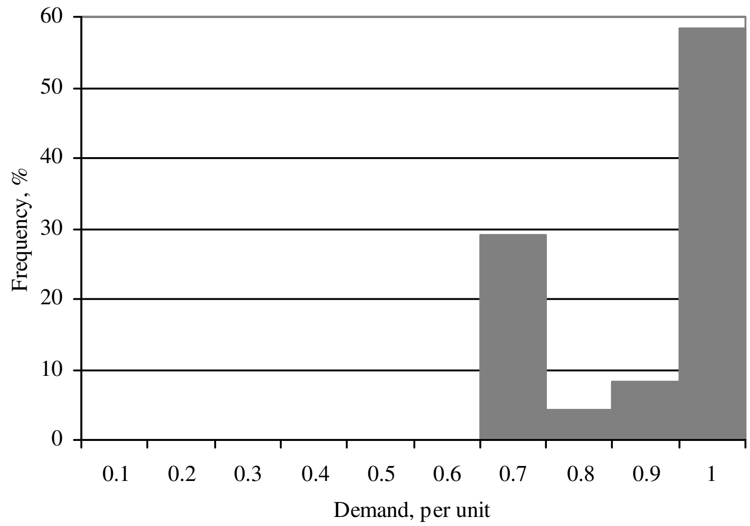

Fig. 7 Demand distribution

d. Scenarios

Scenarios are defined by making assumptions on the siting of flexible generators. The time horizon is 2020, the scenarios contemplate variable energy mixes and loads, and different spatial distributions of these elements in the grid. The key assumption is that in 2020 the target of 20% RES penetration in the energy mix of the triangular area is met, representing approximately 1/3 of the electricity produced by RES. Different installed capacities of the flexible generators in the nodes 2 and 3 as indicated in Table 1 are studied keeping the total installed capacity of these generators close to 650 MW. In addition, the effect of the flexibility constraints is analyzed. Io one case it is assumed that the flexible generator is completely flexible and in another case the generator can change its rated output from 40 to 100%. The latter could be required in electricity systems for spinning reserve purpose.

e. Results

The NEPLAN simulation runs under the above scenarios providing with steady state evaluations of the electricity grid operating conditions, in terms of the load status of the network losses. By comparing the results it is expected to draw conclusions on the most effective position of the flexible generators in the grid and on the amount of the transmission losses to be reduced in the case study.

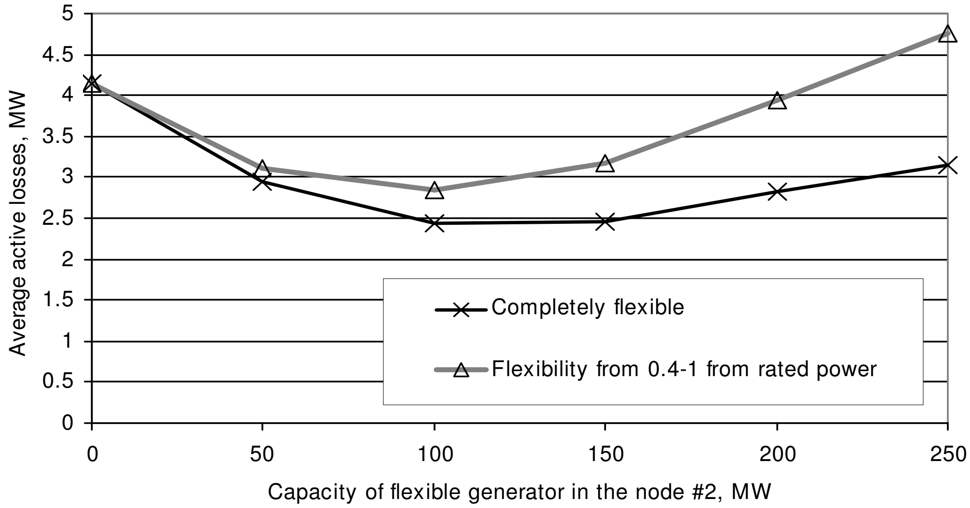

Fig. 8 Average active losses as a function of flexible generation capacity in the node #2 with and without flexibility constraints

Fig. 8 indicates that different capacities of flexible generators could influence the active losses in meshed grids significantly. In our case study, when the flexible generator is completely flexible, the active losses vary from 2.5 to 4.1 MW. Thus in the scenario, where 100 or 150 MW of flexible generator is installed in the node #2 (where also the wind farm is located), the active losses are reduced by around 40% if compared with the scenario with zero flexible generation capacity in the node #2. Besides further increasing of that capacity (above 150 MW) results in the opposite – increase in active losses.

Applying flexibility constraints on rated power change (40 to 100%) the capacity of the flexible generator has similar influence on grid losses. In this case the lowest losses appear when 100 MW of the flexible generator is installed in the node #2. Decrease of losses is a bit lower if compared with the case of completely flexible generator.

In addition, constraints in flexibility increase the peak current in the line 23. It also leads to the increase of flexibility requirements in the generators located in the node #3. Fig. 9 shows these requirements indicating that decrease in generation flexibility in one node (#2) increases the requirements for flexible power in another node (#3) in order to keep power in balance in the system. According our case study by decrease of flexible generation by x MW in one node will require approximately the same amount of x MW in another node. For example, applying flexibility constraints on the 250 MW flexible generator so that the output power can change only in a range 0.4 to 1 from the rated power, the 100 MW of the power plant capacity becomes inflexible (0.4*250 MW = 100 MW). As a consequence additional flexibility of around 100 MW is required from another node (Fig. 9).

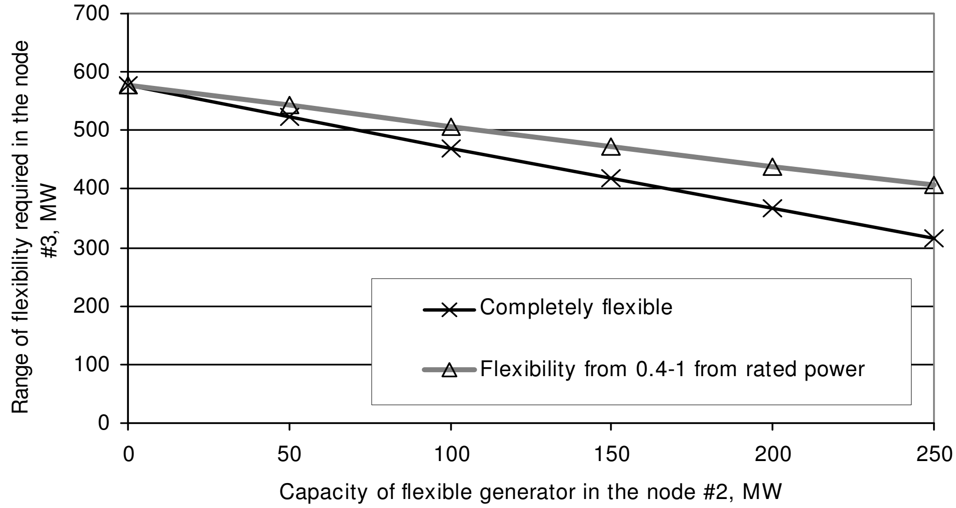

Fig. 9 Flexible power requirements in the node #3 as a function of flexible generation capacity in the node #2 with and without flexibility constraints

5. Conclusions

This study addresses the role of siting of flexible power generators on the active losses in electricity system. Study is performed in simplified meshed electricity grid having three nodes connected through three lines each with other.

In electricity systems containing high share of variable generators (like wind farms) the siting of flexible generators affects the active losses in meshed grids significantly. The case study indicate that active losses could be reduced as much as by 40% through optimization of the electricity system topology.

However, applying flexibility constraints leads to lower possible loss reduction. For example, generator with flexibility constraints on its output from 0.4 to 1 from its rated power decreases the maximum loss reduction to 33%. This decrease of flexibility requires additional flexibility increase in other part in the system.

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Abstract

This report analyses technically the energy saving potentials in electricity grids including both transmission and distribution parts. The focus is on technical active loss reduction in electricity grid through different sitings of flexible power generators (like gas turbines). For the study a simplified triangular shape grid configuration is used containing three nodes connected through three lines each with other. The study area is considered the North Sea due to the relatively high wind power potential. The study results indicate that active losses could be reduced as much as by 40% through optimization of the electricity system topology.

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