Increasing DG Capacity of Existing Networks through Reactive Power Control and Curtailment

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INCREASING DG CAPACITY OF EXISTING NETWORKS THROUGH REACTIVE POWER CONTROL AND CURTAILMENT

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Abstract Renewable energy sources (RES), especially wind turbines, have become more important during the last years. An increasing number of distributed generation (DG) units are connected to weak medium voltage distribution networks in rural areas where they have a large influence on the voltage and the line losses. Voltage rise is in this case often a limiting factor for the maximum amount of DG capacity. Already current wind turbines with a capacity of 2 MW can often not easily be connected to existing 10 kV feeders.

To increase the DG capacity of existing networks without reinforcement DG units can be controlled. This paper proposes abandoning unity power factor used today and letting the converters used as network interface of many new wind turbine generators absorb reactive power to reduce the voltage level. Since reactive power has great influence on losses in the network the use of reactive power is limited. Line losses due to the transfer of reactive power are taken into account in this study. Furthermore the use of curtailment is analysed.

Simulations of voltage change and line losses when using reactive power control by the connected wind turbines and curtailment in a simple test system are presented. Without reinforcement of the network it was possible to increase the DG capacity from 2,7 MW to more than 4 MW in the test network without violating voltage limits. Line losses increase but to a reasonable extent and lost energy due to curtailment is insignificant.

1 INTRODUCTION

This paper discusses the influence of connecting large DG capacity to a weak 7-node power system. Simulations have been done for a grid consisting of underground cables and overhead lines. The focus of the simulations was the voltage at the most remote node, which is node 7, and the possibility to regulate the voltage by absorption of reactive power at this connection point. Three different methods for handling of reactive power were tested: unity power factor, constant $cos\varphi$ but less than unity and a simple regulating algorithm. In cases were it was not possible to keep the voltage below the upper limit with only reactive power, the feed-in of active power was decreased (curtailment) to obtain an acceptable voltage. A simple regulation algorithm for absorbing reactive power and reducing active power to keep the voltage under the upper voltage limit was introduced.

Losses in the distribution system caused by transferring active and reactive power are calculated based on a generic load profile and a measured generation profile. The effect on energy losses due to curtailment and absorption of reactive power is also shown.

2 GRID PROPERTIES

The grid used in these simulations is generic and has two 10 kV feeders as shown in figure 1. One of the feeders is a pure load feeder with a constant power load at node 3. Node 2 is the feeder head and at the same time also the slack bus. Node 1 is part of the feeding network and not taken into account here.

The length of each line between two nodes is 2 km. Underground cables are 95 mm^2 aluminium cables with three conductors. Cable impedance is $\underline{Z}_{cable} = (0,320 + j0,097)\,\frac{\Omega}{\mathrm{km}}$, thus $X/R = 0{,}3$. For simulations with overhead lines a cross section of 99 mm^2, which is a common size in Sweden, were assumed. The impedance of the overhead line is $\underline{Z}_{OH-line} = (0,340 + j0,409)\frac{\Omega}{\mathrm{km}}$ which gives $X/R = 1{,}2$.

Due to the larger X/R-ratio the voltage in a grid with overhead lines is more sensitive to reactive power but even in networks with underground cables reactive power can change the voltage [1] [2]. This fact can be used to control the voltage by delivering or consuming reactive power. Especially the possibility to counteract the voltage rise caused by the MW infeed of DG units seems to be beneficial.

No shunt capacitors or reactances are used and loads are modelled as constant power loads with $cos\varphi = 0{,}95$. The generating units are full scale converter wind turbines with the possibility to deliver and to absorb reactive power with some limitations due to their maximum current. The maximum reactive power which can be absorbed or delivered in this study is 0,5 times the maximum active power (corresponding to a minimum power factor (PF), $cos\varphi = 0{,}89$). A power factor as low as 0,89 can be obtained from standard wind turbines with full scale converter (e g Enercon) and some DFIG wind turbines [3]. Is lower power factor needed wind turbines with STATCOM properties (e g Enercon E-70) has to be chosen.

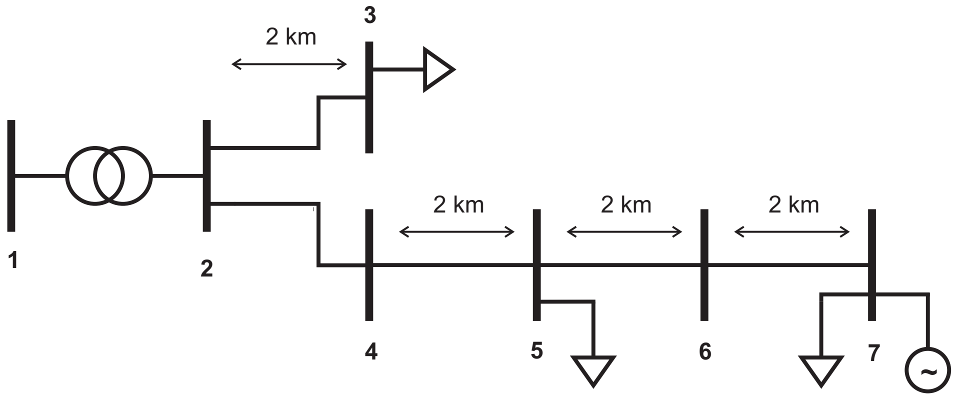


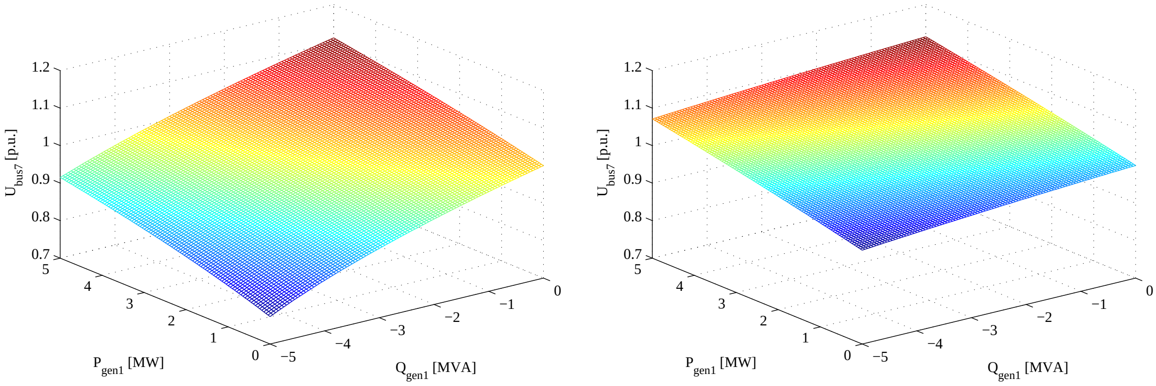
Figure 1 Single-line-diagram of the test system

3 VOLTAGE CONTROL BY AND REACTIVE POWER FROM DG UNITS

Full scale converters become more and more common for new DG units. An advantage of units with full scale converters is the feasibility to inject and absorb reactive power for the most part independent on the output of active power. Therefore in this study it is assumed that reactive power output can be chosen according to the demands of the power grid. There can be different available power modes for control of the active and reactive power from DG units. In island mode it is important to keep the frequency and voltage in the network within the limits (Vf-control) while in grid connected operation normally setpoints for active and reactive power are used (PQ-control) [4]. In this study the PQ-control is used to make the reactive power controllable.

In principle there are at least three different ways to determine the amount of reactive power which should be delivered at a certain time. One possible way which is often preferred by utilities is unity power factor ($cos\varphi = 1$) [5]. In this case the DG units should only deliver active power and not consume or produce reactive power. Another possibility is to choose a constant power factor less than 1 ($cos\varphi < 1$ and $cos\varphi$ $const$) [6]. The third and most flexible way is to use a variable power factor which makes it possible to adapt the reactive power to the actual conditions in the grid. The power factor can be calculated by the controller in the DG unit without need of any communication.

Figure 2 shows the influence of active and reactive power on the voltage at node 7. The impact on the voltage is shown both for overhead lines and underground cables. The voltage at node 7 is lowest when no active power is injected and the maximum value for reactive power, 5 MVAr is absorbed (front corner in fig 2). The highest voltage will be obtained when injecting the maximum amount of active power 5 MW and no reactive power is absorbed (0 MVAr), as it is the case in the furthest corner. When not absorbing or injecting any power the voltage remains unchanged corresponding to the right corner. Due to a higher impedance of the overhead line (figure 2(a)) the voltage is increasing more for this line type compared to the cable (figure 2(b)).



(a) overhead lines

(b) underground cables

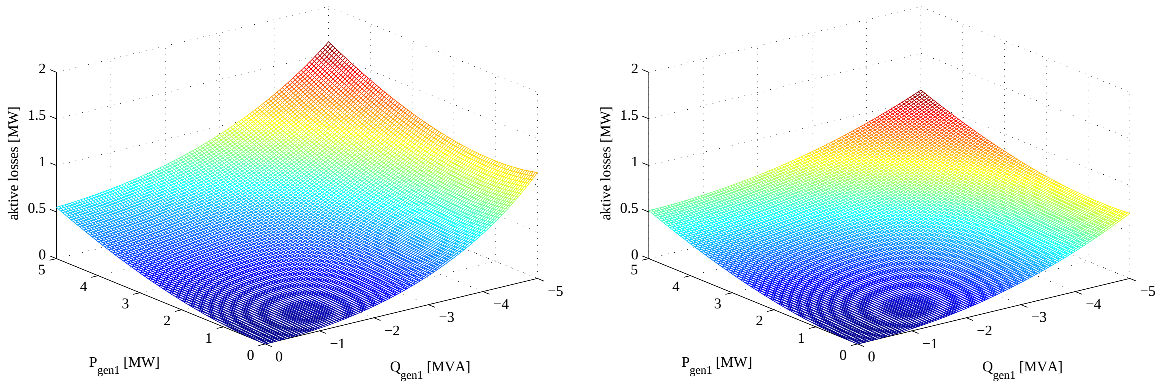
Figure 2 Voltage changes caused by active and reactive power

The scale in which losses will be changed by active and reactive power at node 7 in this test system is shown below. In figure 3(a) the losses are shown for a system with overhead lines and in figure 3(b) the same simulation is shown for underground cables. As expected the network losses are minimal, next to zero, when not transferring any power at all as is shown in the front corner of figure 3(a). Losses are increasing for both transferring active and reactive power. That losses in this case are higher for the overhead line than for the cable is depending on the larger impedance of the overhead line.

4 VOLTAGE CONTROL ALGORITHM

When using DG reactive output to support the grid, the highest priority is to maintain the voltage within acceptable limits. Subsequently the reduction of losses will be taken into account. In this section a simple algorithm to maintain the node voltage will be presented.

The algorithm shown in figure 4 checks if the voltage at node 7, the node where the controllable DG unit is connected, is above the limit or not. If the voltage is below the upper limit



(a) overhead lines (b) underground cables

Figure 3 Loss changes caused by active and reactive power

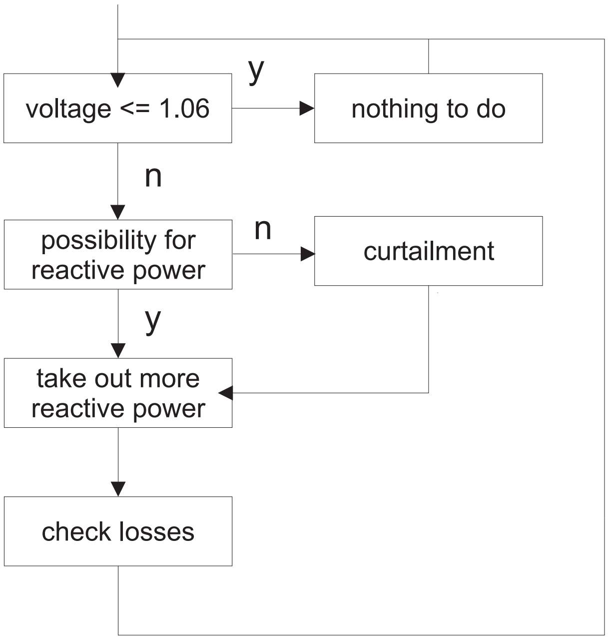


Figure 4 Simple algorithm for voltage control by reactive power

no action will be taken. If action is needed due to violation of the overvoltage limit, it will be checked, if there are resources to consume more reactive power. If this is possible the consumption of reactive power will be raised with one step. Is there no opportunity for taking out more reactive power, the active power will be curtailed. In a last step losses will be checked for the new state.

5 MATPOWER SIMULATIONS

5.1 Simulation parameters

The simulations are done with the simulation tool MATLAB and the MATPOWER [7] scripts. The maximum allowed voltage was according to UK limits [8] [9] and the Swedish standard for low voltage networks (SS 421 18 11 and SS-EN 50160) set to 1,06 p.u.. The used load and generation profiles (figure 5) have a resolution of 10s intervals containing values of 24 hours.

The load and generation curves have a large influence on the total system losses. While the load profile is a pure generic profile, which could be realistic for some shopping centre, the generation profile is based on real measured wind turbine data and scaled to fit the different amounts of maximum active power P_{max}.

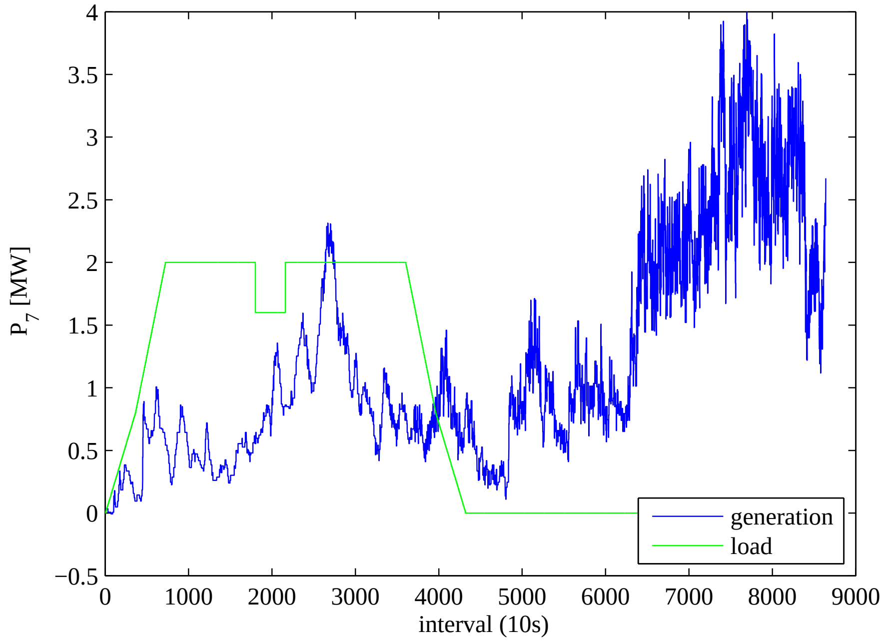


Figure 5 Load and generation profiles used for the simulations

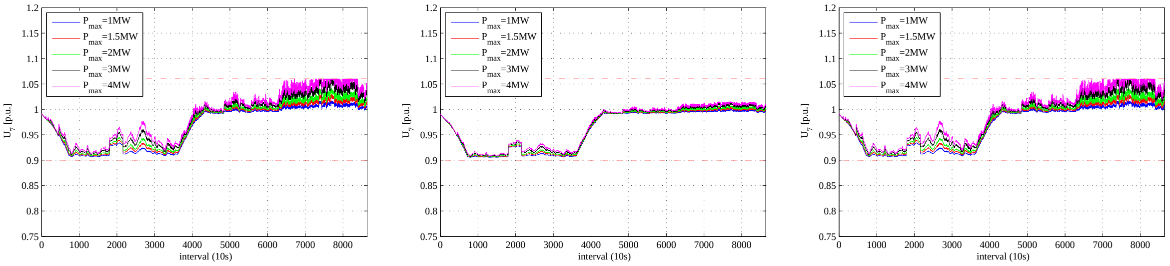
The simulations were done with a varying amount of maximum active power $P_{max} = 1{,}5\,\mathrm{MW}$, $2\,\mathrm{MW}$, $3\,\mathrm{MW}$, $4\,\mathrm{MW}$ injected by the DG unit connected to node 7. Beside the DG unit there was also a load of $2\,\mathrm{MW}$ and $cos\varphi = 0{,}95$ connected to node 7 so that the total active power at node 7 was varying between $-2\,\mathrm{MW}$ and $2\,\mathrm{MW}$. Other loads at the feeders were two constant power loads at node 3 ($P = 2\,\mathrm{MW}$, $cos\varphi = 0{,}95$) and node 5 ($P = 0{,}5\,\mathrm{MW}$, $cos\varphi = 0{,}95$).

The available reactive power consumption from the DG unit at node 7 was $Q_{max} = 0{,}5P_{max}$ (corresponding to a minimum PF=0,89) and the simulations were done for the three alternatives of reactive power presented in section 3. In the case of a constant power factor $cos\varphi = 0{,}89$ was used. The low constant power factor gives maximum impact on the voltage but causes the highest losses. Therefore, in practice also other power factors are quite possible.

5.2 Simulation results - voltage

Voltage control simulations have been done for both a system with overhead lines and with underground cables. For each case the different methods of using reactive power were simulated.

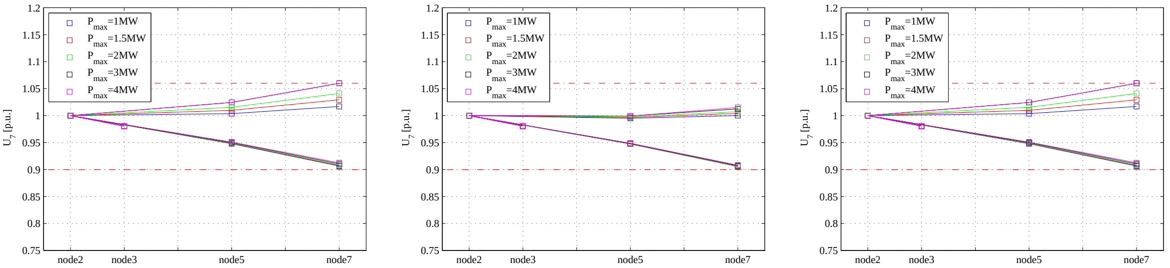
Overhead lines Figure 6 shows the minimum and maximum voltages obtained at node 7 over a simulated 24h period. All three methods are capable to limit the voltage to avoid overvoltages. From figure 6(a) and 6(c) it can be seen that in case of large DG units (P_{max}) curtailment is needed to avoid overvoltage. Here the voltage is reaching the upper limit several times between the time intervals 7000 and 8000. The minimum and maximum voltages at node 7 are close to the limits. In the case of a constant $cos\varphi$ the voltage profile is flatter due to the reactive power increasing at the same time as the active power. In this case no curtailment is needed (figure 6(b)).



(a) $cos\varphi = 1$ (b) $cos\varphi = 0{,}89$ (c) $cos\varphi$ var

Figure 6 Voltage at node 7 in a overhead line network for different types of cos φ

Figure 7 shows the minimum and maximum voltages at all nodes along the feeder over a simulated 24h time period in case of overhead lines.



(a) $cos\varphi = 1$ (b) $cos\varphi = 0{,}89$ (c) $cos\varphi$ var

Figure 7 Minimum and maximum voltages at all nodes along the feeders in a overhead line network for different types of cos φ

The values for the maximum voltage at node 7 according to the different values of the maximum active power P_{max} during a 24h time period are tabulated in table 1. Without reactive power already with a maximum active power output of 3 MW curtailment is needed during some periods of time to lower the voltage. Using a constant power factor of 0,89 is also a possibility in this kind of grid. In this case the X/R-ratio of about 1,2 is leading to an almost constant maximum voltage at node 7 as shown in equation (1) [1] [10]. Even the use of a variable power factor maintains the voltage within the limits but the voltage level is higher for large active power outputs since the algorithm is not reducing the voltage before it reaches the maximum value of 1,06 p.u..

$$\Delta U = \frac{P \cdot R + Q \cdot X}{U_{rec\_end}}$$

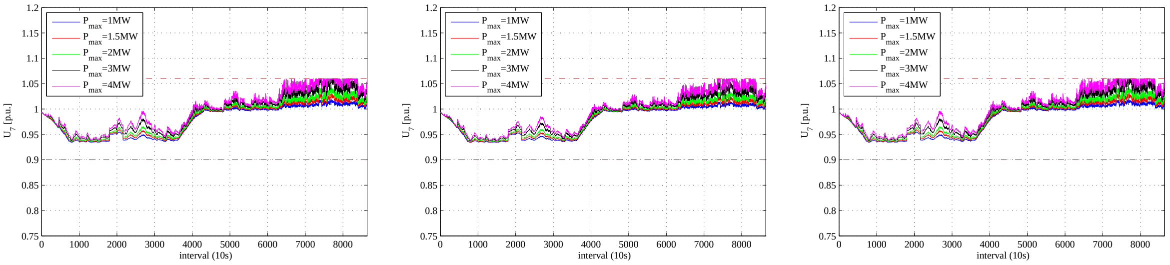
when $\Delta U = 0$:

$$0 = P \cdot R + Q \cdot X \Rightarrow P \cdot R = -Q \cdot X \Rightarrow -\frac{Q}{P} = \frac{R}{X} \tag{1}$$

Table 1 Maximum voltages at node 7 for different types of cos φ on overhead lines (bold values if curtailment used)

P_{max}	U [p.u.] at $cos\varphi = 1$, no curtailment	U [p.u.] at $cos\varphi = 1$, curtailment	U [p.u.] at $cos\varphi = 0{,}89$, no curtailment	U [p.u.] at $cos\varphi$ variable
1	1,017	1,017	1,000	1,017
1,5	1,029	1,029	1,004	1,029
2	1,041	1,041	1,007	1,041
3	1,064	**1,060**	1,012	1,060
4	1,084	**1,060**	1,015	1,060

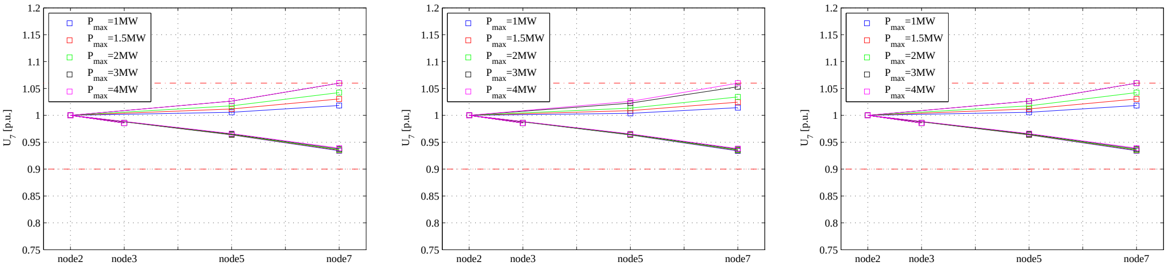
Underground cables In case of underground cables the use of reactive power for voltage is much less efficient than it is for overhead lines due to the lower X/R-ratio. This becomes obvious from figure 8 where it is shown that curtailment is needed even when using a constant power factor of 0,89. The maximum voltages along the feeder (figure 9(b)) are also varying more than in figure 7(b).



(a) $cos\varphi = 1$ (b) $cos\varphi = 0{,}89$ (c) $cos\varphi$ var

Figure 8 Voltage at node 7 in a cable network for different types of cos φ

Figure 9 shows the minimum and maximum voltages at all nodes along the feeder over a simulated 24h time period in case of underground cables.



(a) $cos\varphi = 1$ (b) $cos\varphi = 0{,}89$ (c) $cos\varphi$ var

Figure 9 Minimum and maximum voltages at all nodes along the feeders in a cable network for different types of cos φ

Table 2 shows the maximum voltage at node 7 for the different modes of regulating reactive power and changing maximum active power. Without any reactive power control in this generic network the maximum allowed active power is $P_{max} = 2{,}7\,\mathrm{MW}$ without using curtailment. For higher outputs of active power curtailment must be used at some time. In case of the cable network it is not sufficient to use a fixed $cos\varphi = 0{,}89$ without curtailment for larger active power than $P_{max} = 3{,}3\,\mathrm{MW}$. This due to the small influence of reactive power caused by the low X/R-ratio for underground cables. A variable power factor $cos\varphi$ equivalent to a combination of reactive power and when necessary curtailment is also a possible solution to maintain the voltage below the upper limit.

Table 2 Maximum voltages at node 7 for different types of cosφ in a cable network (bold values if curtailment used)

P_{max}	U [p.u.] at $cos\varphi = 1$, no curtailment	U [p.u.] at $cos\varphi = 1$, curtailment	U [p.u.] at $cos\varphi = 0{,}89$, no curtailment	U [p.u.] at $cos\varphi$ variable
1	1,018	1,018	1.014	1,018
1,5	1,031	1,031	1,024	1,031
2	1,042	1,042	1,034	1,042
3	1,065	**1,060**	1,053	1,060
4	1,087	**1,060**	1,071	**1,060**

5.3 Simulation results - losses

In general DG-units can decrease power losses in a network when their production is leading to less power which needs to be transferred over the lines. On the other hand also increasing losses are possible when the production is not matching the consumption at all. When reactive power is used to maintain the voltage this is normally causing higher losses than without transferring reactive power. Hence losses can also be a limit for controlling voltage by using reactive power. The simulation results presented in this section show the variation in losses for varying active power and different methods of reactive power control.

Overhead lines In table 3 losses in MWh for a time period of 24 hours are shown when using the load and generation profiles from figure 5. The greatest losses are obtained when using a constant power factor less than unity. Without using reactive power the losses, 2,295 MWh (corresponding to 2,9 % of the totally transferred energy), are lowest but this is due to the fact that curtailment is used for larger active power output and therefore the amount of transferred energy is decreasing which is leading to lower losses. A variable power factor permits a voltage close to the upper limit and therefore both less reactive power is needed and constant power load current is lower. These facts influence the losses in a positive manner.

Underground cables The losses for a cable network are shown in table 4. Also in this case the largest losses are obtained when using a constant power factor. Both without reactive power and with a variable power factor the losses are lower. That losses are in general lower for the cable network than for the overhead line network is depending on the lower impedance in the cable network used for this study.

In table 5 the total amount of available wind power and the impacts of the different power factors are shown. The total energy flow in the test system during the simulated time is 79,2 MWh caused by the loads and additional up to 28,9 MWh from generation. For a smaller amount of installed wind turbine capacity (e.g. 2 MW) it is possible to feed-in all the available wind energy to the grid independent of the power factor. For the network used in this study the rated power

Table 3 Network losses for different types of cosφ in an overhead line network - Reference value for losses without any DG connected 2,463 MWh

P_{max}	E [MWh] at $cos\varphi = 1$, no curtailment	E [MWh] at $cos\varphi = 1$, curtailment	E [MWh] at $cos\varphi = 0{,}89$, no curtailment	E [MWh] at $cos\varphi$ variable
1	2,176	2,176	2,272	2,176
1,5	2,103	2,103	2,265	2,103
2	2,075	2,075	2,317	2,075
3	2,144	2,144	2,592	2,145
4	2,373	2,295	3,093	2,385

Table 4 Network losses for different types of cosφ in a cable network - Reference value for losses without any DG connected 2,210 MWh

P_{max}	E [MWh] at $cos\varphi = 1$, no curtailment	E [MWh] at $cos\varphi = 1$, curtailment	E [MWh] at $cos\varphi = 0{,}89$, no curtailment	E [MWh] at $cos\varphi$ variable
1	1,958	1,958	2,029	1,958
1,5	1,896	1,896	2,020	1,896
2	1,876	1,876	2,061	1,876
3	1,951	1,950	2,291	1,951
4	2,172	2,086	2,708	2,241

P_{max} of the DG unit at node 7, operated at unity power factor, must not exceed 2,74 MW in a network consisting of cables respectively 2,72 MW in an overhead line network without violating the upper voltage limit. When using a constant power factor of $cos\varphi = 0,89$ active power up to 3,34 MW in a cable network and 4,85 MW in an overhead line network can be injected without violating the upper voltage limit. However for larger capacities the power delivered to the network must be curtailed during some time in order not to violate the upper voltage limits when using unity power factor. Even if losses are increasing by transferring more reactive power there is a benefit in using reactive power to control the voltage to some extent. However, increasing losses limit the maximum DG capacity P_{max} when using reactive power for voltage regulation whereas curtailment can be used without technical limitations but it will be limited by economical reasons.

Since it is possible to transfer the maximal available wind energy for a capacity up to 2,7 MW without violating the voltage limits it is reasonable to do it with a unity power factor. When larger DG capacities are installed it is necessary to take measures for limiting the voltage.

When installing wind power with a maximum capacity of 4 MW in the test network consisting of underground cables 0,733 MWh of wind energy is curtailed during a day when load and generation are like in figure 5 and a unity power factor is used. In this case are around 2,5 % of the pontential wind energy lost. For the same DG capacity it is possible to limit the voltage by using a constant power factor $cos\varphi = 0{,}89$ and nearly no curtailment (0,069 MWh) would be needed but in this case the losses are increasing with 0,536 MWh compared to the case where curtailment and unity power factor are used. 1,9 % of the potential wind energy can not be used for this reason. However, using a variable power factor nearly all wind energy is used (−0,044 MWh) and the losses due to the additional transfer of reactive power is only 0,069 MWh. Hence only around 0,4 % of the total available wind energy are lost. The benefit

Table 5 Energy from DG units and losses

line type	overhead line		underground cable	
P_{max} of DG unit	2 MW	4 MW	2 MW	4 MW
Uncurtailed energy from DG units	14,461	28,921	14,461	28,921
Obtained energy with $cos\varphi = 1$	14,461	28,312	14,461	28,188
curtailed wind energy	0,000	0,609	0,000	0,733
increase of losses	0,000	-0,078	0,000	-0,010
Obtained energy with $cos\varphi = 0,89$	14,461	28,921	14,461	28,852
curtailed wind energy	0,000	0,000	0,000	0,069
increase of losses	0,242	0,720	0,185	0,536
Obtained energy with $cos\varphi$ variable	14,461	28,921	14,461	28,877
curtailed wind energy	0,000	0,000	0,000	0,044
increase of losses	0,000	0,012	0,000	0,069

from using a variable power factor instead of unity power factor and curtailment is the difference between the lost production in the case of unity power factor and curtailment and the extra losses due to transferring reactive power with variable power factor, in the studied case this will be $0,733 - 0,069 - 0,044 = 0{,}620\,\text{MWh}$. Figure 10 shows a summary of the losses caused by the transfer of reactive power versus the amount of wind energy which can not be used due to curtailment for the different methods of voltage control.

Table 5 shows that the result in case of a network with overhead lines is about the same. The generally larger losses for this network are depending on a larger line impedance. Worth noticing is also that more curtailment is needed in the case of underground cables compared to overhead lines. This is reasonable as the power factor of the loads is less than unity and therefore the loads have a larger influence on the voltage in the case of overhead lines.

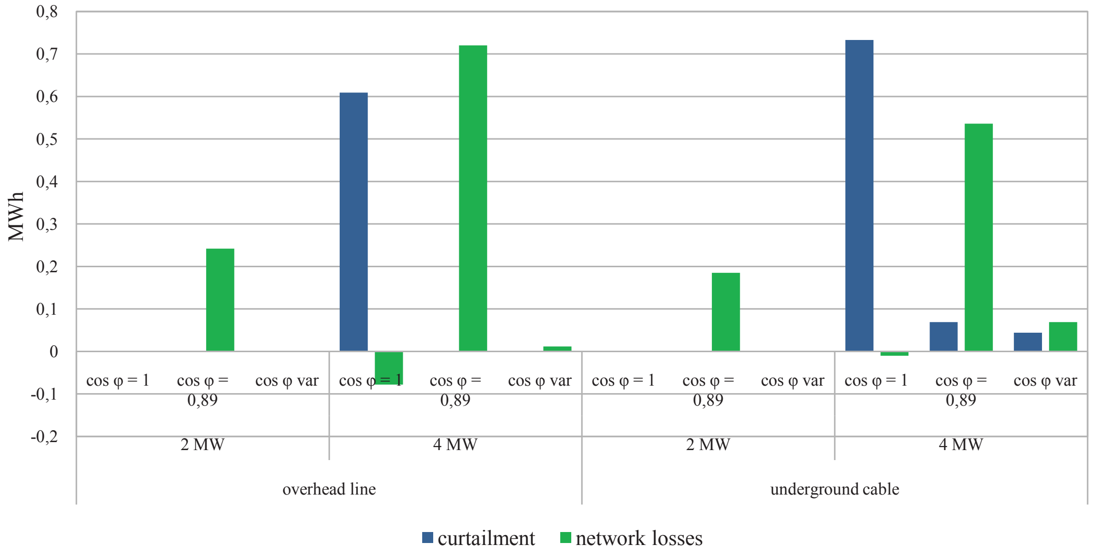


Figure 10 Curtailed energy and increase in network losses for the simulated cases in MWh

6 CONCLUSIONS AND RESULTS

The poor lines in this study are leading to a large amount of total losses. Even if the lines used are undersized in relation to the active power, which should be transferred and the network would not have been designed like this from the beginning, there may occur practical situations where the conditions are similar to the ones in this study.

The simulations in section 5.2 show that voltage control with reactive power is more efficient for overhead lines than for underground cables due to the higher X/R-ratio which is about 1,2 for the used type of overhead line and only around 0,3 for the cable type used in the presented networks.

Besides the positive effect of high flexibility in voltage control there are also disadvantages of using reactive power. In all cases transfer of reactive power causes an increase of power losses. As shown in table 3 and 4 the losses are largest in case of a constant power factor. The reason is that during most time more reactive power is transferred than needed to maintain the voltage.

As shown in this study a variable power factor provides an opportunity to increase the DG capacity without violating the voltage limits and even reducing the losses in the network. Both in an overhead line network and in a cable network it was possible to increase the DG capacity from 2,7 MW to at least 4 MW by introducing a variable power factor and curtailment instead of a constant power factor $cos\varphi = 1$. In this case the total energy delivered by the DG unit was increasing.

Benefits for the total delivered energy from the DG units minus the losses added by reactive power compared to curtailment were only obtained when a variable power factor was used in a cable network. Both for a constant power factor and for a variable power factor in an overhead line network the losses were not less than when using power factor $cos\varphi = 1$ and curtailment when needed. This may change in case of larger lines and different load and generation profiles.

For the cases presented variable power factor seems to be the most favourable method. Benefits from a variable power factor are lower losses and fast control. In future work OLTC will be integrated at the primary substation to obtain a more realistic test system. Also the new generation of energy meters is planned to be used for indicating over or undervoltage at customers side.

An algorithm to determine the absorption of reactive power in each node and for control of the OLTC will the be applied. Also the priority between tap changes, reactive power absorption and curtailment has to be determined.

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