Electricity Meters for Coordinated Voltage Control in Medium Voltage Networks with Wind Power

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Abstract—During the last years the amount of electricity generated by Distributed Energy Resources (DER), especially wind turbines, has been increasing a lot. These Distributed Generation (DG) units are often connected to rural distribution networks, where they have a large impact on the voltage and the network losses. The network voltage at the customers point of connection is an important quality criteria and has to follow different standards as e.g. EN 50160. Therefore the voltage change caused by the integration of production units in the distribution network is an important aspect when integrating more DG in distribution networks and often a limiting factor for the maximum DG capacity which is possible to integrate into an existing network without reinforcement. Using the available voltage band more efficiently by applying coordinated voltage control is a possibility to increase the hosted DG capacity in an existing distribution network without reinforcement of the network. To get the actual network status the new generation of electricity meters, which have the feasibility to communicate real time voltage measurements from the customers side to a network controller, give some benefits to a more flexible and coordinated voltage control in the network. The voltage range in the network will be used adapted to the actual load and generation situation instead of using worst case assumptions as it is good practice until now. A main part of the voltage control in medium voltage distribution networks is done by the on-load tap changer (OLTC) which takes the voltage at the consumers point of connection into account. A generic 10 kV distribution network with three typical types of feeders, as pure load, pure generation and mixed load and generation feeder, has been outlined. Coordinated voltage control is implemented by a central voltage controller. Simulations on the voltage and the network losses have been done and will be presented in this paper. The maximum DG capacity in the test system increases most when introducing coordinated control of the OLTC but also the use of reactive power adds some benefit. Further increase of the DG capacity by more extensive use of curtailment is always possible but due to economical aspects not favoured.

Index Terms—coordinated voltage control, distributed generation (DG), distribution network, electricity meters.

I. INTRODUCTION

Due to several reasons the number of small generation units has been increasing during the last years. In contrast to traditional power plants the DG units are mostly connected to the electricity distribution network on medium or low voltage level. This fact is changing the requirements on the so far mainly passive distribution networks.

In the past distribution networks were planned and build for transferring energy from the transmission network, where the large power stations are connected, to the customer. The energy flow was unidirectional and without any extra equipment the voltage was decreasing from the substation to the customers connection points. With integration of production units in the distribution grid, Distributed Generation (DG), this voltage drop along distribution network feeders can no longer be seen as a matter of course under all circumstances. Especially when the generation on a feeder is larger then the load a voltage rise along the feeder can occur too. But due to different standards as for example EN 50160 the voltage change at the costumers point of connection is limited to ±10% of the nominal voltage during 95% of the time of a week. This long term limit is generally also valid for medium distribution networks but the network operating companies are often using more strict limits. In practice the limits for the voltage change caused by DG units can be limited to ±2.5% respective ±5% of the nominal value depending on the type of feeder the DG unit is connected to. The voltage rise is depending on the amount of injected power and therefore it is a limiting factor for the DG capacity that can be integrated in an existing network without changes. Today usually unity power factor is aimed when connecting distributed generation to a medium voltage network [1]. For maintaining the network voltage this rule does not have to be the best solution under all circumstances. Consuming reactive power which corresponds to an inductive power factor less than unity has also been suggested in the literature [2].

Voltage regulation in medium voltage distribution networks is mainly done by an on-load tap changer situated at the substation transformer. In most cases the configuration of the OLTC is done to maintain the voltage at the substations medium voltage side constant, thus counteracting voltage changes at the transformers primary side and the voltage drop in the transformer which is varying with the load. The voltage set point at the OLTC has to be chosen regarding to the maximum (worst case) voltage drop between the substations busbar and the end of the most affected feeder. Therefore the voltage at the substation busbar is during most of the time higher as needed to fulfil the voltage requirements but advantageous regarding losses when a major part of the loads are of constant power type. When introducing generation the high voltage level can be harmful especially during times with low load and high generation. For the integration of DG units it would therefore be preferable to adjust the voltage to the actual network situation instead of assuming the worst case but this is not possible with the traditional OLTC control depending.
only on the substation bushbars voltage.

When integrating generation into a distribution network a more flexible voltage regulation would be preferable to enlarge the voltage range which is available for the DG units. To control the voltage in medium voltage networks with reactive power in the same extent as in high voltage transmission networks is not suitable because of the lower X/R-ratio which makes the use of reactive power much more inefficient [3] [4]. The losses will increase a lot while the influence on the voltage is low but even depending on the kind of network. Typically overhead lines have larger X/R-ratio than underground cables. However, the use of reactive power may be suitable in some cases when considering the increase of losses. Due to the structure and properties of medium voltage networks the most effective mode of voltage regulation is, as discussed before, the OLTC. To fit the needs of integrating generation in a distribution network the voltage control by the OLTC can be improved by using real time voltage data from the customers point of connection instead of the substations busbar voltage. The real time voltage measurements are for example available through the new generation of electricity meters which have been installed during the last years. Thus the needed infrastructure is, at least in some countries, already in place. Also the control of active power, curtailment, can in some extent be used to control the voltage. Since that implies waste of DG energy it can only be used to a limited extent.

Going from passive to active distribution networks the traditional view on minimum and maximum values in worst case scenarios can be extended when the actual status of the network is known. If for example real time data for the voltage at the consumers point of connection is available a wider part of the voltage band may be used and thus the voltage can be controlled to fit the specifications instead of presuming the worst case as it has basically been done so far. This seems to be one way to handle larger variations in consumption and generation in distribution networks and thereby increase the maximum hosted DG capacity in a network and will be presented in this paper.

II. TEST SYSTEM

For this study a generic medium voltage network with a rated voltage of 10 kV was used. A single line diagram of the network is shown in figure 1. With a feeder length of at least 8 km the network is typical for a rural area. Even though rural networks are often consisting of mixed overhead line and underground cable feeders in this case underground cables are assumed. The loads are aggregated to the nodes 4, 6, 12, 14 and 16. Generation units are placed at the buses 8, 10, 14 and 16.

A. Network data

The network is fed by an 130/10 kV transformer with an integrated on-load tap changer.

The feeders in the network represent three typical types of feeders in a distribution network. The upper feeder is a pure load feeder with loads connected at bus 4 and bus 6. These loads are constant power loads at 1,0 MW and 1,5 MW with a power factor of 0,95. The middle feeder is a pure generation feeder with two DG units (e.g. wind turbines) connected. Their rated capacity is at 1,0 MW for the unit at node 8 and 2,6 MW for the unit connected to node 10. The lower feeder is a mixed load and generation feeder with three loads at node 12 (1,0 MW), node 14 (0,5 MW) and node 16 (1,0 MW) as well as two generation units at bus 14 (1,0 MW) and bus 16 (2,6 MW).

Each line between two nodes has a length of 2 km and consists of 95 mm² aluminium underground cable resulting in an impedance of $Z_{section} = 2 \cdot (0,320 + j0,097) \Omega$ per line section. The dimensions of the lines in the network are quite close to the rated values, limited by thermal conditions, which is not corresponding to the criteria for economical dimensioning. A network would not have been dimensioned like this from the start but after some years and increasing installed DG capacity it may be a reasonable situation and an alternative to run the network like this instead of reinforcing which implies installing new cables.

B. Electricity meters

Since July 2009 billing on at least monthly measurement readings is compulsory for the utilities in Sweden and due to that the country is one of the first with 100 % coverage of new generation electricity meters from which data is remote readable. Therefore some kind of communication is needed between the customers energy meters and the utility. Beyond transferring monthly measurement readings the new type of electricity meters are able to supply more information. It is for example possible to send alarm messages when the voltage limits at the customers side are violated. In a more advanced version of the meters or with some modifications it would also be possible to measure and submit the voltage magnitude at the customers side. With this installed infrastructure it is for the first time possible to get real time measurements of the voltage and the consumed power at the customers side.
This data can be used for improving and ensuring the voltage quality for the customer. But as it will be shown in this paper, the data can also be used to optimise the network operation of the distribution system.

III. VOLTAGE CONTROL

The voltage magnitude and the stability of the voltage at the customers point of connection is an important quality criteria. This paper is focusing on voltage fluctuation in a medium voltage distribution network. Voltage changes are mainly caused by load and generation variations. The requirements to the voltage are defined in different standards as e.g. EN50160. For a distribution network it means that the voltage has to be within ±10% of the nominal voltage in at least 95 percent of the time in a week.

There are different methods to control the network voltage, also depending of the voltage level and the type of network. Some methods that can be used in a medium voltage distribution network will be described here.

A. On-load tap changer

On-load tap changers (OLTC) are normally placed in the transformer between the high voltage and medium voltage network and they are quite common to maintain the voltage in medium voltage networks. The tap changer changes the voltage by alternating the turns ratio of the transformers primary and secondary side. OLTC are used for compensation both for voltage changes from the upper high voltage grid and for voltage changes caused by load flow changes in the medium voltage network. The extensiveness of voltage regulation is limited by the number of positions and the step size between the positions. Common values for on-load tap changers are ±9 steps and a step size which is changing the turn ratio with 1.67%.

An advantage of the OLTC is the possibility to change the voltage in the whole network behind the transformer without adding extra losses beside those which can arise from the current change which will follow the voltage change. Furthermore the OLTC can both increase and decrease the voltage within some limits. Changing the voltage in the entire network is also a drawback since there may be both feeders with low and feeders with high voltage at the same time. In this case a tap change makes the situation more worse in one of the feeders. Thus the possibility of maintaining the voltage only by a tap changer is limited especially in networks where there are different feeders with various characteristics. Other disadvantages are the abrasive wear and required maintenance due to the fact that the OLTC is a mechanical component. This can be handled by limiting the number of tap changes to reasonable values. In practice it is done by introducing a dead-band and a delay time for the movements of the tap changer.

B. Reactive power

Injection or consumption of reactive power in some nodes is also a way to influence the voltage. Especially in high voltage transmission networks it is common to maintain voltage with shunt capacitors or reactors but even in medium voltage networks voltage can be changed by the use of reactive power. The efficiency of this method is highly depending on the X/R-ratio of the lines. A larger X/R-ratio makes the use of reactive power much more effective as shown in equation (1), where $U_{\text{rec\_end}}$ is the voltage at the receiving end. In case of DG units the amount of reactive power which can be injected or consumed is depending on the type of network connection they have. Modern wind turbines are often connected to the grid via full-scale converters. The reactive power for such units can be controlled freely and for the most part independent on the active power output.

$$\Delta U = \frac{P \cdot R + Q \cdot X}{U_{\text{rec\_end}}}$$ (1)

Using reactive power for voltage control is favourable for punctual voltage control at some nodes. The voltage changes caused by the injection or consumption of reactive power will decrease significantly with the distance. Furthermore, the amount of reactive power can be controlled continuous and therefore also the voltage changes will be continuous. Especially in cable networks, which are generating some reactive power, the consumption of reactive power by DG units may also have some value by reducing the need of shunt reactors. A drawback of voltage control with use of reactive power is the increasing current in the lines and thereby an increase of the network losses.

C. Curtailment

Curtailment, restricting the amount of active power injected in a network node, is only a method to lower the voltage. During times when the network voltage becomes to high due to a large amount of active power fed-in into the grid, one solution to keep the voltage below the upper limit is to reduce or at least limit the active power. This can be done for each controllable unit and affects at most the node where the generation unit is connected.

In case of distributed generation this method will not be favoured since it decreases the energy output from the DG units and thereby make them less competitive. However, it may be a suitable method in some cases where the lost energy is less expensive than a reinforcement of the network. This situation may occur when curtailment is limited to a small part of the total power during periods of high DG generation when the price for electricity is low. Theoretically, when using curtailment, there is no limit for the capacity of DG units connected at some node in a network but broad use of curtailment under longer time periods will not be profitable.

IV. SIMULATIONS

The simulations presented in this paper were done with the simulation tool Matlab and the power flow scripts M At-Power [5] in version 4.0. The simulated time was two days (48 hours) and the voltage in each network node as well as the total network losses were calculated in one minute time steps. The load and generation profiles used for the simulation
are shown in figure 2. The shape of the profiles is assumed
to be the same for all loads and generation units and it is
scaled up to fit the capacity of the various units connected to
the network. Input data for the simulations are the active and
reactive power consumed and injected in the nodes and the
on-load tap changer position which determines the voltage at
the substation busbar.

A. Voltage Control Algorithm

As shown in figure 3 there are three modules for the voltage
control. The use of the voltage control modules is scheduled
by the coordination controller. In this case the highest priority
was set on module 1, the on-load tap changer, so it would
act first when the voltage exceeds the limit in at least one
of the network nodes. When it is not possible to improve the
voltage more by using the OLTC, module 2, reactive power
control, with the next highest priority, is activated and the
reactive power output of the generation units is changed to
maintain the voltage. If over voltage is detected in any
node with generation connected after using module 1 and module 2,
the third module, curtailment controller, is activated and the
active power output is limited. After moving the
on-load tap changer a delay timer is started to prevent the OLTC from
moving back and forward all the time what otherwise could
have happened in some situations.

2) Reactive Power Controller (Module 2): When over volt-
age is detected at a node where a controllable DG unit is
connected and the reactive power controller is activated the
consumption of reactive power at the actual network node
is increased with one step, according to
of the units
maximum reactive power absorption, if there is still some
reactive power capacity available. In case of under voltage
the controller checks if reactive power still is consumed by
the DG unit and then decrease the consumption of reactive
power.

3) Curtailment controller (Module 3): If the curtailment
controller is activated by the coordination controller and over
voltage is detected at a node with active power injection, the
output of active power in the respective node and all other
nodes with generation connected to in the same feeder is
decreased with one step.

B. Procedure

The simulation have been run for different scenarios. While
the type and the properties of the physical network have been
remained unchanged the simulations were done for various
levels of control. For the connected DG units three different
power factor modes were assumed. The first mode was with
unity power factor, which means that no reactive power can
be consumed. In a next step a constant power factor of
inductive was chosen. In that case the DG units where
consuming reactive power corresponding to around the half of
their actual active power output. That seems to be a reasonable
value for the maximum reactive power consumption of modern
wind turbines connected to the grid via full-scale converter as
e.g., Enercon E-70. In the most advanced case a variable power factor was assumed. Here can the amount of reactive power consumed by the DG units vary between zero \((PF = 1)\) and the half of the maximum active DG power \((Q = -0.5 \cdot P_{\text{rated}})\). These cases were also run with traditional OLTC settings with a nearly constant voltage at the substations busbar and with an OLTC controlled by the coordination controller. For getting reference values both the case of pure load and pure generation in the network were run too.

V. RESULTS

The basic values of the major simulation cases are shown in table I.

In the first column the case of a traditional network with only load connected is shown. Since no generation units are connected to the network, the voltage is largest at the substation busbar and below that value at all other nodes of the network. To compensate for the voltage drop in the network and achieve a sufficient voltage level at the most remote node, the voltage set point at the substation busbar has to be set above 1.0 p.u.. In this case one OLTC step (1.017 p.u.) are necessary.

When also connecting the generation units as described in II-A and applying the load and generation profile from figure 2 only about the 80% of the available DG energy can be used. The rest, corresponding to 22.5% has to be curtailed to fulfill the voltage requirements. Anyhow, due to the generation close to the loads the network losses decrease from 4.7% to 2.7% of the total transferred amount of energy. Because of the fixed voltage at the substations busbar there are no OLTC steps based on the load and generation change in the medium voltage distribution network.

In the third column the coordinated control of the on-load tap changer, and thereby the voltage of the substations busbar, is activated, too. Now the available voltage range is used more efficient and therefore the largest part of the DG energy can be absorbed by the network. But still have 3.2% of the available wind energy to be curtailed. Since more energy is transferred through the network, 196.5 MWh compared to 176.5 MWh before, the network losses are increasing to 3.3% but they are still below the value for a pure load network. Now, when using a controlled on-load tap changer, there are 26 OLTC steps during the period of 48 hours.

Changing the power factor of the DG units from unity to 0.89 inductive decreases the voltage at the network nodes where the DG units are connected and hence the capability of injecting more active power to the network increases further. Curtailment is only needed for 1.0% of the total available DG energy. Since in this case additional 53.2 Mvarh of reactive power have to be transferred through the network, the losses are increasing to 4.0%. Thus the largest part of the energy increase from DG units is lost again in the network. Nevertheless, as a benefit from the lower voltage level cause by the consumption of reactive power, the number of on-load tap changer steps is decreasing from 26 to 14.

If the DG units are using a variable power factor and conventional OLTC are applied, the need of curtailment decreases from 22.5% to 10.6% compared to unity power factor. But due to the fact that 32.6 Mvarh of reactive need to be consumed to maintain the voltage, the network losses are increasing from 2.7% to 3.5%.

In the sixth column both the use of a variable power factor by the DG units and a coordinated OLTC control are activated. In that case all the available wind energy can be injected into the medium voltage distribution network without violating the voltage limits. The reactive power consumed by the DG units is varying between 0 Mvar and 0.5 \cdot P_{\text{rated}} that also may result in a power factor less than 0.89 if the voltage at a node is high during at time when the DG units output is below the rated value. Totally 4.7 Mvarh of reactive power are used to maintain the voltage. The network losses for this case are 3.4%. As in the case with unity power factor and controlled OLTC there are 26 OLTC steps during 48 hours.

The minimum and maximum voltages in table I are in some points of the limits of 0.95 p.u. respectively 1.05 p.u.. That phenomenon is well-founded in the fact that the algorithm is reacting on voltage limit alarms. After getting the alarm at 0.95 p.u. or 1.05 p.u. it takes at least one sample for the algorithm to adjust the voltage again. During this time voltage dips and peaks can occur but they are still within the limits of the voltage standard (0.9 p.u.-1.1 p.u.). Furthermore, they could be eliminated by setting the limits for the algorithm closer.

In table II are the key values for the various power factors shown. Up to 3.3 MWh more energy are obtained from the DG units when using a variable power factor instead of unity. From the number of tap changes a constant power factor of 0.89 seems to be favourable but the network losses are increasing in this case.

The resulting voltage curves for the voltage at node 16 over a time period of 48 hours are shown in figure 4. The first subfigure shows the voltage in a pure load network and traditional on-load tap changer settings. In the second subfigure the voltage is shown for DG units connected with unity power factor and traditional OLTC settings. In the first two subfigures the substation voltage is set according to the traditional rules so that the voltage is high during times of low load and low, but not below 0.95 p.u., during times of high load. The marginal for a voltage rise without violating the upper limit is therefore very small during times of low load. This becomes obvious from the long time period where the voltage is at the upper limit around hour 20 and hour 45. In the last subfigure the voltage is shown for a coordinated controlled OLTC and DG units with variable power factor. Due to the controlled OLTC the voltage at the substations busbar is lower during times of low load and generation. In this way a larger part of the total available voltage range is used and therefore more DG energy is absorbed by the network.

VI. CONCLUSION

Concluding from the results in the previous section implementing real time voltage measurements from the customers point of connection and using them for a more flexible control of the on-load tap changer seems to be advantageous. With the
new generation of electricity meters which were installed in Sweden and other countries during the past years the most part of the needed equipment is already in place, even if upgrades are necessary to obtain real time measurements. To minimise the data volume only measurements from the most exposed customers are needed.

Using the on-load tap changer controlled by real time values increases the maximum installable DG capacity in a medium voltage distribution network. A limiting factor for the use of the on-load tap changer is the wear for which reason the number of OLTC steps during a time period has to be considered. By the use of the OLTC the voltage is changed in all nodes of the network, since an improvement obtained in some nodes by changing the OLTC position can downgrade the conditions in other network nodes.

In the shown test system the injected energy from the connected DG units running at unity power factor can be increased from 80,5 MWh to 100,5 MWh during a period of 48 hours when using a controlled OLTC. The number of on-load tap changes caused by the voltage control of the coordination controller is increasing from 0 to 26 steps during 48 hours. The OLTC steps caused by voltage changes in the overlaying network and the voltage drop in the transformer not included.

Consuming reactive power is also a way to reduce the voltage in network nodes where controllable DG units are connected. Due to the associated increase of network losses there are limits for the use of reactive power in a medium voltage distribution network. By using a controlled OLTC and reactive power consumption by the DG units with a constant power factor of 0,89, the maximum injectable DG energy without violating the voltage limits increases to 102,7 MWh. But at the same time the increase in losses caused by the transfer of reactive power is at about two thirds of the increase in injected DG energy. Therefore this method seems not to be a good solution in this case.

By the use of a variable power factor all available DG energy 103,8 MWh is transferable to the network and no more curtailment is needed. Since the losses are increasing compared to unity power factor and the amount of additional injected active power is low, this solution may be too complex compared to the advantage.

The exact number for the benefit from using a on-load tap changer with coordination controller or reactive power consumption to lower the voltage is depending a lot on the network topology and how the load and generation profile are fitting together. For the use of reactive power the X/R-ratio
Fig. 4. Voltage profiles with and without data from electricity meters

has a large impact on the efficiency of that method.

In the future it may be interesting to improve the algorithm and also use real time voltage magnitude values instead of alarms when violating the limits. If even active and reactive power load values are available in real time, power flow calculations are possible and a more optimal network state can be calculated. Later also controllable loads and voltage increase by injection of reactive power should be considered to optimize the system more.

Also a combination of coordinated control and local control is possible. This would reduce the dependency of communication by switching back to the traditional worst case settings of the OLTC and local control of the connected DG units when loosing the communication.

REFERENCES


