SERIES AND PARALLEL SWITCHED INDUCTORS MANAGING STEADY-STATE OVERVOLTAGES IN DISTRIBUTION GRIDS WITH DISTRIBUTED GENERATION

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ABSTRACT

The rising amount of distributed generation (DG) connected to distribution grids may lead to overvoltages in steady-state. Reactive power provided by DG or inductors can reduce voltage. This paper investigates how series and parallel switched inductors can be used to reduce overvoltages at the medium voltage level. The issues of the inductor's size and position are discussed. Fields of application and required devices for an operation are derived. The effects on voltage level and voltage stability are investigated. The economic benefit is evaluated by a comparison of possible efforts to manage overvoltages. A probabilistic approach was used. The results show that series switched inductors provide a flexible and cost-efficient solution. The parallel inductors are more expensive, but still cheaper than conventional grid reinforcements. Compared to series inductors, parallel inductors can be used independently from grid structures and the spread of DG in the distribution grid.

INTRODUCTION

The amount of DG in distribution grids increased enormously in the last years. In times of low load and high power feed-in by DG, steady state overvoltages can occur frequently [1]. Especially rural areas are concerned. This leads to a decline of voltage quality. Protection devices of DG trip quite often. Efficient solutions are needed to manage voltage. Grid reinforcements can resolve the problem, but are linked with high investments. Knowing neither the real network conditions nor the further development of installations of DG, it is not clear if these costs are really necessary and rewarding. Cheaper and more flexible solutions are demanded. DG providing reactive power could do this, but sometimes its control is not possible or only has a limited range, especially when older devices of DG are installed. The application of series and parallel switched inductors in the medium voltage level is investigated in this paper, since it may provide an alternative solution as desired. The basic idea is that inductors shall be installed and only switched on in case of overvoltages.

ANALYSIS AND METHODOLOGY

Technical premises

The voltage limit for steady state is given by the European standard EN50160 [2]. The voltage must not exceed +10% U_n regarding 99% of 10-minute mean RMS values in grids at the medium and low voltage level. Furthermore the thermal capability of devices should not be exceeded. Since a reduction of voltage is coupled with a rise of current, the application of inductors in order to drop voltages is limited by the rated current of devices.
According to a German guideline, voltage changes caused by switching actions of DG at the medium voltage level should be limited by 2% U_n [3]. As one aim of this paper is to include DG into the existing grid structures, this criterion was considered as a ΔU limitation for switching actions of inductors during the simulations.

Methodology

The application of inductors is investigated by regarding an exemplary rural grid, whose main characteristics are presented in Table 1.

Table 1 Grid characteristics

Nominal voltage	20 kV
Grid topology	single-branch
Peak Load	3.8 MW
Installed DG	up to 13.1 MW, concentrated
Distance DG ↔ substation	25 km
Type of line	Overhead 94 Al, I_r = 350 A

Fig. 1 shows a simplified single-line diagram of the simulated grid. In the regarded case DG is represented by a wind farm which is connected at one node. The effects on voltage quality have been analysed by static load flows. A probabilistic approach was used to be able to consider all possible states by their probability. Therefore real recreated profiles of loads and wind energy converters based on measurements have been used.

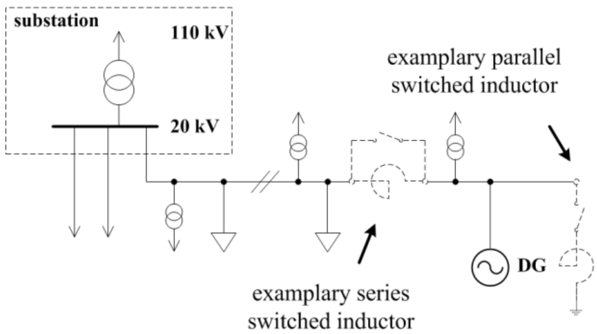

Fig. 1 Simplified single-line diagram of the simulation network. A possible installation of inductors is shown.

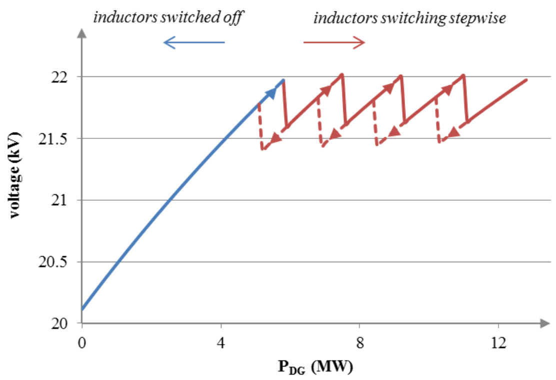

Fig. 2 Voltage at the most distant node with DG while using parallel inductors in times of min. load

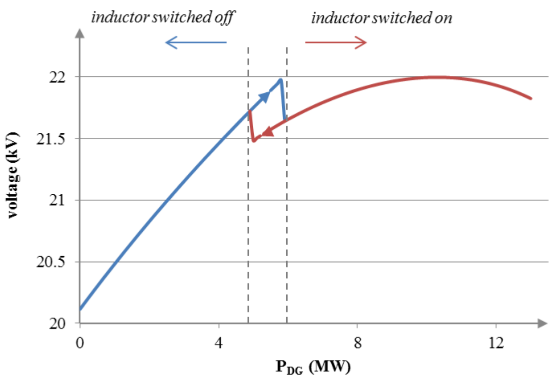

Fig. 3 Voltage at the most distant node with DG while using series inductors in times of min. load

Application of parallel switched inductors

The application of parallel switched inductors is already common for reactive power compensation. The voltage dropping effect can also be achieved by DG providing reactive power. Due to their parallel assembly, parallel switched inductors can be applied independent of the existing grid topology. The node with highest voltages turned out to be the most effective position for the parallel inductors. The required inductances ranged from 500mH up to several thousand mH. In case of a wide operation range and a ΔU limitation for switching actions, a variation of the inductance is needed as shown in Fig. 2. Coils with iron core and a discrete step solution have been chosen, due to compact design and relatively low prices.

Application of series switched inductors

The voltage dropping effect of series switched inductors is similar as occurring at highly loaded overhead lines on the high voltage level. Thereby the normal power flow from the node with controlled voltage to nodes with uncontrolled voltages causes a voltage drop over the line. In case of inverse power flow, from nodes with uncontrolled voltages (DG) to the node with controlled voltage (substation), a reduction of voltages at the uncontrolled nodes is achieved.

Field of application

Series switched inductors can only be applied in non-meshed parts of a grid. Otherwise the inductor would be partly short-circuited and the voltage-dropping effect is reduced enormously. Application fields are open-ring networks, single branch networks and DG with high rated power, which can be connected via the series inductor.

Required devices

In the simulations, series inductances in the range from 10 to 40 mH range have been required. This can be realized by using air-cored coils. In general, one inductor per phase was sufficient to keep the voltage below the tolerable bounds, as shown in Fig. 3. A stepwise solution was not necessary. Higher power feed-in by DG causes a higher voltage drop by the inductor, as the voltage drop over the inductor depends on the current. From the apex of the curve, the voltage drop caused by series inductance increases even stronger than the voltage rise caused by DG feed-in. The voltage starts decreasing with further power feed-in.

The series inductors can be switched by parallel circuit breakers. As switching criteria the voltage at the most distant node with DG was chosen, which in general is the most critical node regarding overvoltages. To reduce the number of switching operations, a switching hysteresis was applied. Surge arresters should be considered on both sides of the inductors to protect the grid in case of current chopping.

Position and size of the series inductors

Fig. 4 shows the local node voltages for different positions of the inductor. Thereby the inductor is sized in order to limit the voltage at the most distant node from the substation with DG. In this case, an installation next to DG would cause overvoltages on the grid-side of the inductor. This can be avoided by sizing the inductor according to the voltage on the grid-side of the inductor. This "oversizing" leads to lower voltages at the node with DG, related to increasing current and losses.

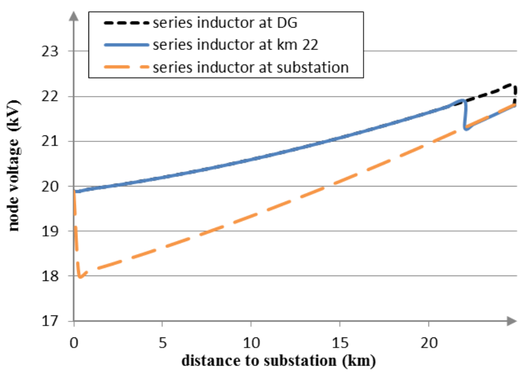

Fig. 4 Voltages for varying position of series inductors in times of min. load and max. DG feed-in

Another solution can be achieved by a closer position of the inductor to the substation. The extreme would be an installation at the substation itself like shown in Fig. 4. This can even lead to unpermitted low voltages. In order to minimize losses during the simulations, the series inductor was positioned 2.8 km in front of DG, 22 kilometers distant to the substation.

RESULTS

Effects on voltage quality

Voltage level

The effect of the inductors on the voltage level is shown in Fig. 5 in the situation of min. load and max. DG feed-in. At the most distant node, where the DG is located, the voltage is reduced by more than 1,6 kV. The voltage curve with series inductors shows a voltage drop at the position of the coil. The higher the power feed-in, the higher becomes the voltage drop over the series inductor. Although this voltage curve is unconventional, the voltage of every node can be kept below the limit in every case of power injection and load.

Voltage stability

Switching inductors in series with the power line results in lower short circuit power at all nodes on the far-side of the inductor. The influence of changes in active and reactive power load on voltage has to be regarded especially for the nodes on the far-side of the inductance. The highest variation is expected at the most distant node with DG for a local change of load. Fig. 6 illustrates the change of voltage for a given change of active load at the most distant node with DG in dependence of DG feed-in. It is visible that the application of parallel inductors has no impact on the voltage sensitivity for changes of active load. The short circuit power is not affected by parallel inductors. When using series switched inductors, dV/dP crosses zero and even gets to positive values with increasing power feed-in. Looking back on Fig. 3, the maximum of the voltage curve can be detected as the zero-

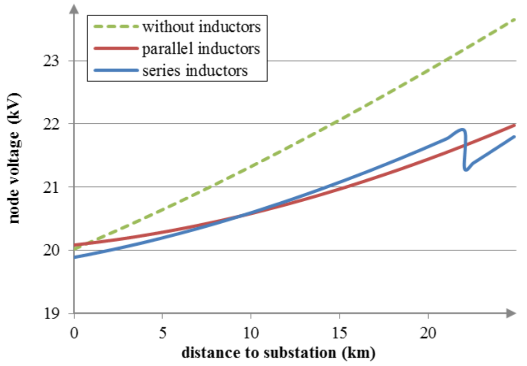

Fig. 5 Voltage spread on the grid in times of min. load and max. DG feed-in

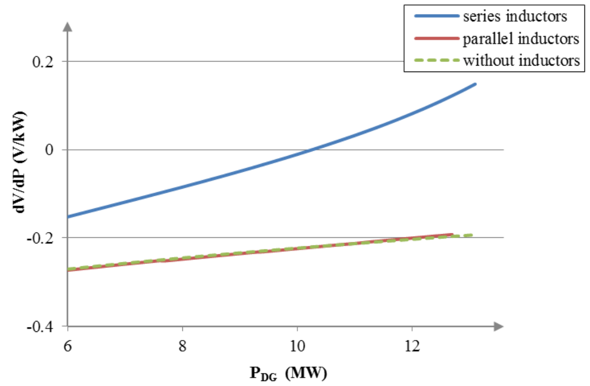

Fig. 6 Voltage sensitivity at the most distant node for local variation of active load

crossing point in Fig. 6. In fact, Fig. 6 illustrates the negative derivation of Fig. 3 for series inductors. As the absolute value of dV/dP with series inductors stays below the absolute value without inductors, the application of series inductors does not worsen voltage sensitivity for active load. Instead series inductors improve the voltage sensitivity for active load.

The influence of changes in reactive power on voltage is shown in Fig. 7. In the application of parallel inductors, the influence of dQ is slightly stronger compared to an operation without inductors. The parallel inductors already provide reactive power, thus further inductive load has a stronger impact on voltage. Furthermore the inductance steps get visible. Regarding the series inductors, it has to be distinguished between a change of reactive power on the grid-side and on the DG-side of the series inductance. The impact on voltage of a dQ on the grid-side is nearly the same as observed with parallel inductors. In this case, the reactive current does not flow through the series inductor and its influence remains low. In case of a dQ on the DG-side of the inductor, the influence on voltage is distinctly higher. Therefore the variation of reactive power "behind" the inductor should be limited when the series inductor is switched on. This may already be provided by the following reasons:

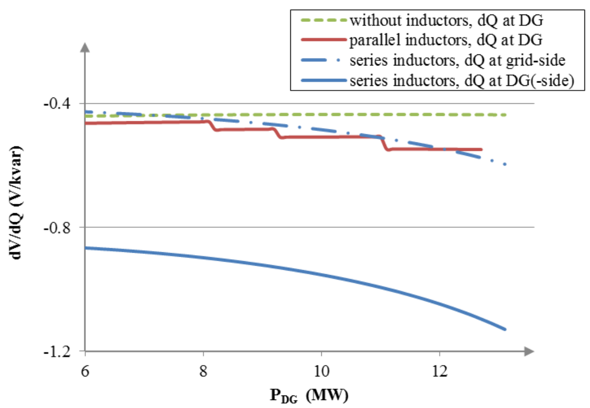

Fig. 7 Voltage sensitivity at the most distant node for variation of inductive load

- The inductor is located relatively close to DG. The amount of loads and connected low voltage networks in between the DG and the inductor remains low.
- The series inductors are mostly switched on in times of low load. In this case the reactive power caused by local transformers and its variation can be considered as low.

Otherwise the possible variation of reactive power on the DG-side can be reduced by closer position to DG. If series inductors are installed between the point of common coupling and the DG, the influence of reactive power variation is minimized. In this case, the series inductors have to be oversized as previously described.

Economic evaluation

The economic benefit of the application of series and parallel switched inductors is visualized in Fig. 8. Conventional grid reinforcements, such as an installation of additional lines are regarded as a reference for the comparison of the results. As grid reinforcements provide reduced line losses, this is considered in terms of costs for additional line losses for the applications with inductors. The application of series inductors turns out to be the most cost-efficient solution. The stepless realization with air-cored coils leads to low investment costs. These investments remain constant since a series inductor of one discrete size is able to control the overvoltages among the whole power width. The parallel inductors have higher investment costs, because they use coils with iron cores and require several steps with increasing DG. However, both inductor solutions have an increasing amount of costs for line losses, since the benefit of a reduced line resistance with grid reinforcements impacts stronger with increasing power transmission. Thereby, parallel inductors provide slightly higher currents than series inductors, because they actively inject reactive power in parallel circuit. Thus, series inductors enable to connect more DG than parallel ones.

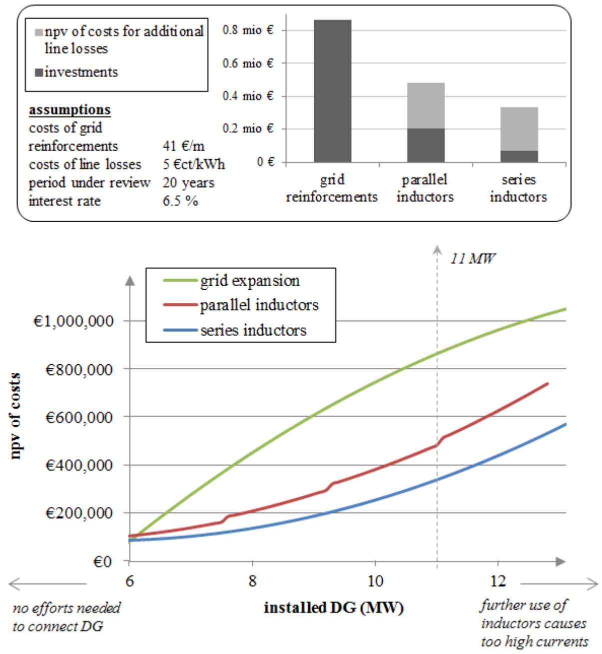

Fig. 8 Net present value (npv) of efforts in order to include DG without stationary overvoltages in dependence of installed DG

CONCLUSION

The application of inductors was presented in an exemplary distribution grid at the medium voltage level. The aim was a reduction of steady-state overvoltages caused by DG. Series inductors provided a reduction of voltages with low investments and high flexibility in the simulation. Nevertheless, the reduction of short circuit power at distant nodes has to be considered. One inductor could manage the voltages over a wide range of power. If the amount of DG should increase unpredictable after the installation of the series inductor, further actions are still not necessary until a certain amount of DG is reached. These results are applicable to other medium voltage grids. The higher the distance to substation and the amount of cabling, the bigger is the economic benefit compared to grid reinforcements. However, the structure of the grid has to be suitable, as series inductors are not applicable in meshed grids with spread DG. In this case parallel switched inductors can provide a better solution. The application in low voltage grids is also assumed to be profitable but should be investigated individually. In cases where DG causes overvoltages but cannot provide further reactive power, series and parallel switched inductors are a promising alternative.

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