UNCONTROLLED REACTIVE POWER FLOW DUE TO LOCAL CONTROL OF DISTRIBUTED GENERATORS

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ABSTRACT

The central issue of this paper is the analysis of the reactive power behaviour in the presence of distributed generation and the outline of a method to control and dynamically optimize the reactive power flow.

Results show that the local control of the decentralized reactive power produces an uncontrolled reactive power flow in the high voltage grid and changes the static behaviour of the load seen from it. Under these conditions, the coordinated operation of the medium and high voltage grid is essential to maintain efficient and safe operation of the power system and to facilitate further DG integration.

The implementation of the Volt/var secondary control in high and medium voltage levels upgraded with the relevant static and dynamic constraints maintains the reactive power flow and the voltage in both voltage levels within acceptable limits and opens the door for the dynamic optimization of the grid.

INTRODUCTION

Distributed Generation (DG) penetration is increasing continuously in all voltage levels of distribution networks. In many cases, the production capacity dispersed on it has reached a critical mass (i.e. more than 50% of the total production capacity). Under these conditions a notable uncontrolled reactive power flow in high voltage grid have been observed /1/.

Many projects have been implemented to study the DG integration however, the effects of the Volt/var interdependencies between high and medium voltage grid were not apparent and consequently have hardly been investigated. There are two reasons why this interdependency was not in focus: firstly, each research project is normally restricted to an individual model region, which means to only one HV/MV intersection point. Figure 1 a) shows a typical model region embedded within the power grid and the corresponding uncontrolled reactive power ΔQ that is injected from the medium voltage grid (MVG) into the high voltage grid (HVG) through the supplying transformer. Secondly, the DG share on the model region was limited. These two factors have limited the uncontrolled reactive power flow in a minimum and as a result, the impact on the HVG were not visible. However, in the case of a large scale DG penetration, it is observed that from each HV/MV intersection point a notable uncontrolled reactive power is injected into the HVG, Figure 2b). Under those conditions, the Volt/var interdependencies between HVG and MVG become apparent and dangerous /1/.

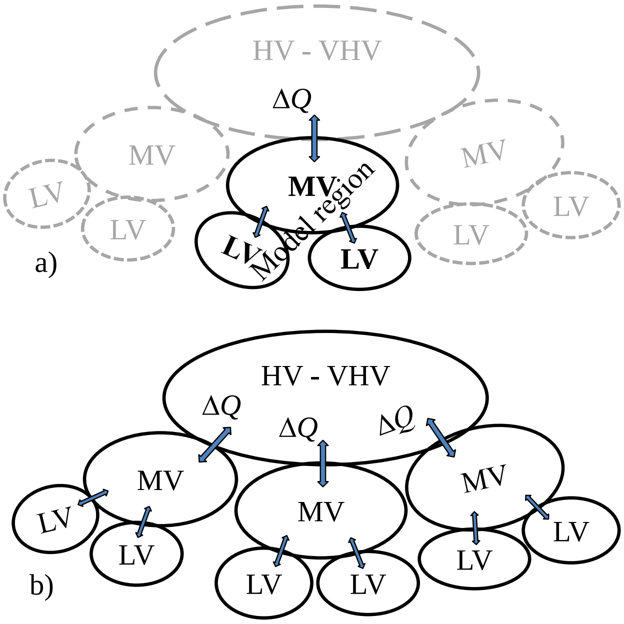

Fig. 1. General overview of the power grid: a) uncontrolled reactive power in the case of a typical model region; b) uncontrolled reactive power in the case of a large DG share on the whole power grid.

This paper shows some of the results from the research project ZUQDE (Central Volt/var Control in presence of decentralized generation) /2/, from another perspective: the interdependencies of Volt-vars. Firstly the global and local effect of the vars injection in MVG on the voltage profile of a feeder is investigated. The effect of the inverters PQ diagram (which connects the PV and wind energy resources to the grid) on the uncontrolled reactive power flow is examined in detail. Secondly, the impact of the local control behavior $Q(U)$, - implemented at the PV facilities at the low voltage grid (LVG) - on the uncontrolled reactive power and on the load-voltage behavior of the feeder lumped load is investigated carefully. Finally, to resolve the adverse effects of DGs integration, a method to control the reactive power flow through the HV/MV transformers is outlined.

VARS FLOW BY MEANS OF MVG

The ZUQDE project was performed in Salzburg, Austria, /2-4/. Within the project framework the voltage was controlled automatically and the network operation was being dynamically optimized in real time. Automatic voltage control was realized based on the distribution system state estimator (DSSE) and the Volt/var control (VVC). Both DSSE and VVC were integrated in the

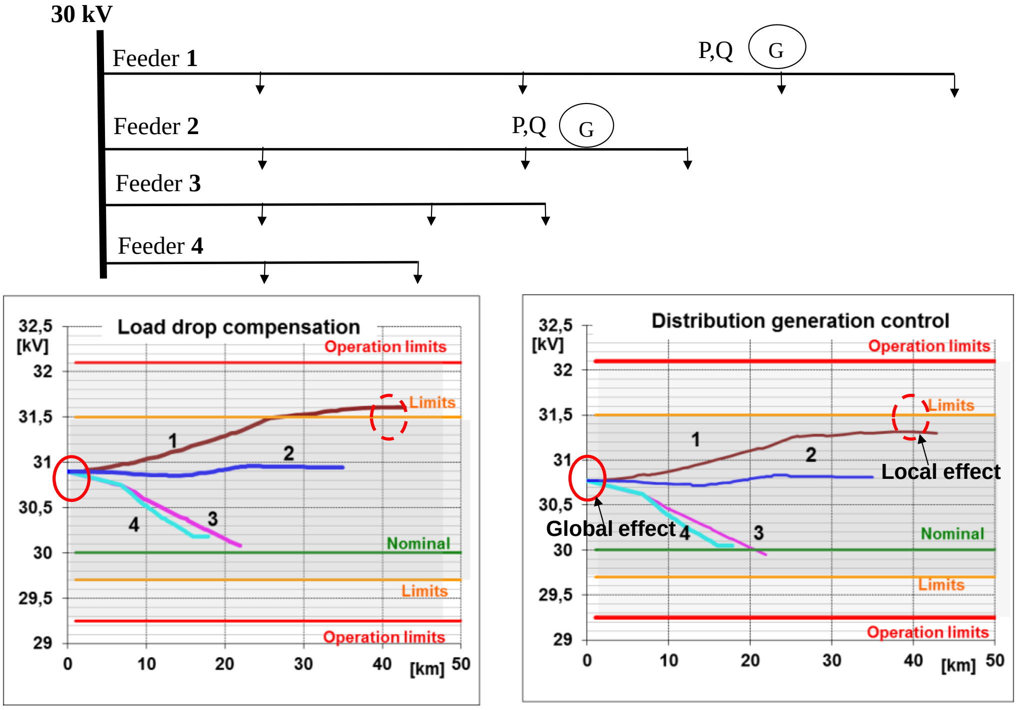

Fig. 2. Voltage profiles of 4 real feeders under: a) normal operation conditions and b) distribution generator control (source /2/)

SCADA system. Four "run of river" power plants, connected to the 30kV medium MVG of the Lungau region, were upgraded with reactive power primary control. Under normal operation, they are operated with seasonal-dependent load factor cosφ, however during the project, these rules were neglected and the reactive power set point was sent from a secondary control by taking into account the *PQ* diagrams of the generators. To avoid any mal-operation during the project the voltage limits were set at a more conservative level than the normal operational values. Figure 2 shows the voltage profiles of 4 representative real feeders calculated by DSSE under a) normal operation conditions – load drop compensation - and b) after the DGs control (the transformer step position remained unchanged). Two "run of river" power plants (DGs) were connected to the feeders 1 and 2. Feeders 3 and 4 were pure load feeders. By comparing the voltage profile of feeder 1 before and after the DGs reactive power control we founded that the reactive power control had a considerable local impact on the voltage at the injection point (connection point of DG) - approximately 280V. Furthermore, a global effect was observed. The voltage on the feeder head bus bar was shifted by 80V. Additionally, a reactive power flow change of about 5% through the supplying transformer was observed.

For a better understanding of this phenomenon some simulations have been carried out which comprised a 110kV line, a 110/33kV transformer, and a 33kV feeder with cable structure. The distributed generators were simulated through one 6MW equivalent generator connected almost at the end of the feeder. Figure 3 shows the effects of the reactive power injection on the voltage profile. Two cases were simulated: In the first case the generator injected only active power (6MW, cosΦ = 0).

The voltage at the end of the feeder (35.382kV) is observed to be 5.7% higher than at the start of the feeder (33.495). In the second case, the generator injected 3Mvar inductive power (6MW, cosΦ = 0.89). The voltage on the injection point was observed to decrease by 4.086kV corresponding to the local effect. The voltage on the 33kV feeder head bus bar was decreased by 1.995kV and corresponds to the global effect. The reactive power change on the transformer was 3.4Mvar. The increase of 0.4Mvar has to be attributed to the decrease of the reactive generation of the cables due to the voltage decrease. The flow of the 3.4Mvar on the 110kV line caused a voltage decrease of

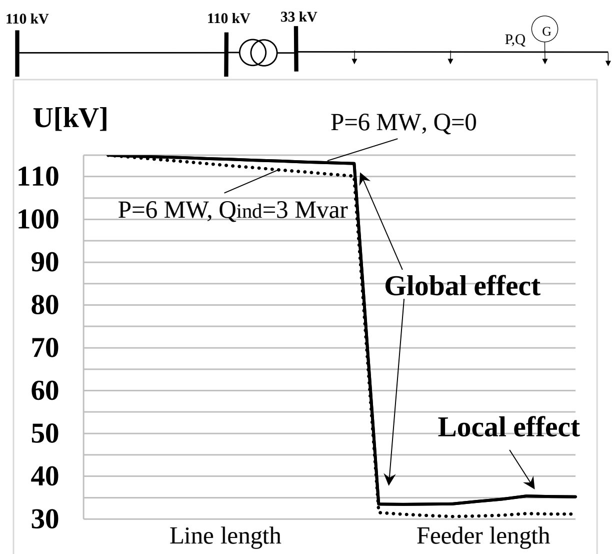

Fig. 3. Effects of the reactive power injection on the voltage profile.

2.95kV at the 110kV bus bar of the transformer.

This all shows that beside the local effect of the reactive power injection in a radial structure, there exists also a global effect which is apparent when the share of DGs increases in all distribution grids. The Volt/var interdependencies between different voltage level grids are very complicated because of the OLTCs reaction. This requires further, more detailed, investigations.

An additional uncontrolled reactive power amount is observed to flow into the HVG in the presence of DGs which are connected to the MVG through inverters. Figure 4 shows a typical MV radial network with DGs connected through invertors. The PQ diagram of an inverter is also shown. According to the Grid Codes requirements, the inverter is set to inject power at a constant power factor, e.g. 0.95. Normally, all units that are using volatile energy resources, are characterized by a fluctuating real power generation. Being operated with constant power factor, the fluctuation of the real power will be also passed over to the reactive power, i.e. for a power factor of 0.95, a real power fluctuation of 80% will provoke a fluctuation of the reactive power on the HVG, of about 20%, as can be seen from Figure 4. The limit extension from 0.95 inductive/capacitive to 0.9 inductive/capacitive as mentioned in /5/ will produce a larger uncontrolled, additional reactive power amount in the HVG. Hence for a power factor of 0.90, a real power fluctuation of 80% will provoke a fluctuation of the reactive power on the HVG, of about 35%, see Figure 4.
In conclusion the volatile nature of the primary resources also causes an uncontrolled reactive power flow on the HVG. This is estimated to be the reason for the severe uncontrolled bi-directional reactive power flows through the HV/MV transformers observed in Western Denmark in 2003 /1/.

VARS FLOW BY MEANS OF LVG

Recently, the PV installation on building roofs has become very popular. However experience has shown that

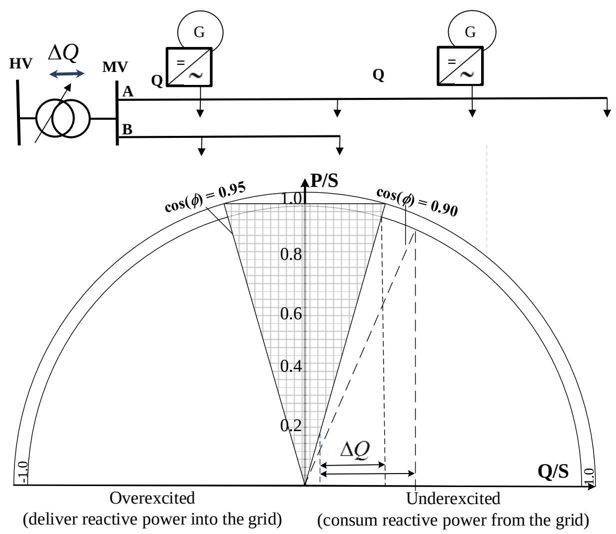

Fig. 4 PQ diagram of an inverter through which are connected PV and wind energy resources

to a certain extent they cause voltage problems on the LVG. The upgrade of the PVs with $Q(U)$ controllers

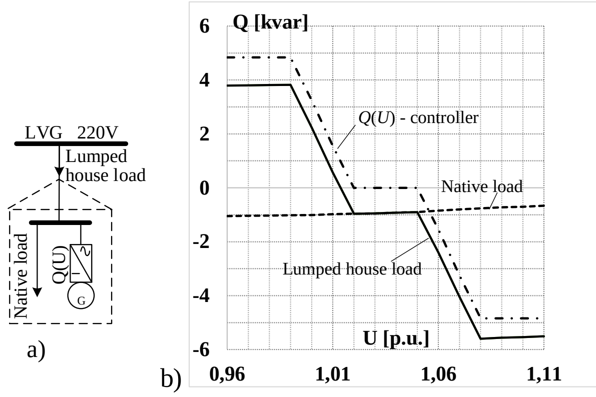

Fig. 5 Prosumer overview and its reactive power voltage sensitivity: a) Schematic representation b) Dependency of the reactive power from the voltage

should resolve this voltage challenge /6/. Further analysing this case, besides the reactive power flow change on the MVG and then respectively in the HVG another phenomenon has been detected: the natural behaviour of load vs. voltage seen from the HVG (lumped feeder load) is considerably modified.

Figure 5 shows an overview of prosumer and its reactive power voltage sensitivity. Figure 5 a) shows a schematic presentation of the prosumer/lumped house load, which is a composition of the native load (e.g. the pure house hold loads) and the PV inverter which is upgraded with a $Q(U)$ controller. Figure 5 b) shows the dependency of the reactive power from the voltage for the native load with a voltage sensitivity of K_{QV} =3, for the $Q(U)$ controller as given by /6/ and the lumped house loads composition. The lumped house load is a composition of the behavior of the native load and of the $Q(U)$ controller. The traditional lumped house load is a composition of the $Q(U)$ behavior of each native load. The native load behavior is characterized by a static load characteristic K_{QV} =0.6 – 3.1, /7/. However, in the presence of the $Q(U)$ controller the composed lumped house load behaviour is considerably modified. The $Q(U)$ controller introduces a significant nonlinearity into the behavior of the lumped house load. Parts of the curve have become steeper. Indeed the result of the recently reported field tests /8/ have shown higher voltage sensitivity values (K_{QV} =3.1 – 8.8) than the usual ones.

LVG is normally connected to the MVG through transformers with fixed steps, indicating a rigid methodology. All effects on LVG will be reflected on MVG. Figure 6 shows the reactive power through a HV/MV transformer for the maximal load with or without PV injection into LVG as a function of the voltage on the MV supply bus bar as calculated by /6/. During the simulations it was assumed that PVs were installed in each house roof. 100% PV injection means, that there was a sunny day and all installed PVs were in operation. Traditionally, lumped feeder loads (load seen from HVG) are presented as composite load models on the basis of constant power, current and impedance. However, from Figure 6 it can be clearly seen, that in the presence of PVs equipped with $Q(U)$ local controller, the natural behavior load vs. voltage seen from HVG (lumped feeder load) is considerably modified. The local control behavior $Q(U)$ of the PV has been superimposed on the natural load-voltage behavior and the curve has obviously become steeper. This can create serious voltage stability problems on HVG. Further investigations are necessary to explore the impact of the high PV share on LVG, on the lumped house and feeder load vs. voltage behavior.

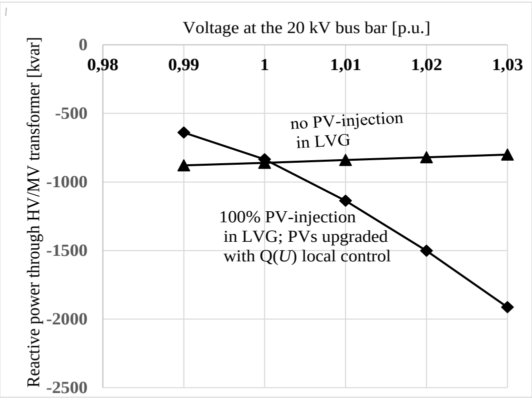

Fig. 6 Reactive power through HV/MV transformer for the maximum load with or without PV injection at LVG as a function of the voltages on the MV supply bus bar

OPTIMIZED OPERATION HVG/MVG

As detailed above, the required reactive power in distribution grid causes serious problems on the operation of the HVG. Therefore, a method to control the reactive power through the HV/MV transformers is outlined in the following.

In the framework of the ZUQDE project, the operation automation was realised by means of primary and secondary control. Figure 7 illustrates the control schematic as realized and operated in the framework of ZUQDE. The DGs reactive power and the transformer steps were set under the primary control. Secondary control was realized by means of the VVC, where the control variables were: the reactive power of DGs and the voltage on the feeder head bus bar. The two main objective functions utilized were:

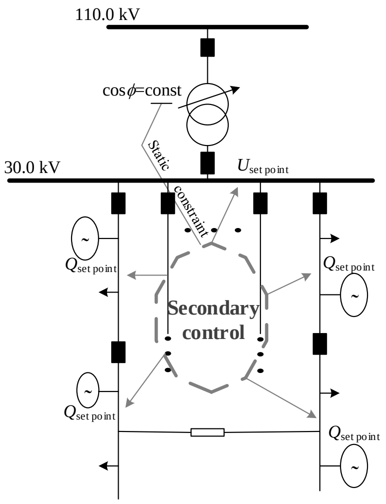

Fig. 7. Control schematic realized and operated in the framework of ZUQDE project

- *Distribution subsystem active power loss* — Minimize the sum of power losses in lines, transformers and capacitors:

$$Obj_1 = \min(\Delta P) = \Delta P^L + \Delta P^{Tr} + \Delta P^C \qquad (1)$$

- *Distribution subsystem power demand* — Minimize the sum of the power losses and customer demand:

$$Obj_2 = \min\left(P^{Dem}\right) = \Delta P + \Sigma P_i^l(V_i) \qquad (2)$$

Whereby the objective functions are subject to the following constraints:

Voltages at all buses are within the limits

$$V_{\min} < V < V_{\max} \qquad (3)$$

Reactive power of all generators are within the corresponding PQ diagrams:

$$-Q_{\min} < Q < Q_{\max} \qquad (4)$$

Transformer steps should be within the limits:

$$Step_{\min} \leq Step \leq Step_{\max} \qquad (5)$$

To maintain control of the reactive power flow through the supplying transformer the following static constraint was set /3, 10/

$$\cos\varphi_{SupplTr} = const. \qquad (6)$$

To facilitate dynamic optimization of the operation of HVG and MVG and to offer ancillary services such as reactive power to HVG the controlling schematic presented in Figure 8 is proposed.

Figure 8 shows the control schematic for the coordinated operation of the medium and high voltage grid. Two secondary control areas type are foreseen. The one operates on the HVG which is under the administration of the one utility. It is hence confined on the high voltage borders with other utilities on the one hand, and with the HV bus bar of the supplying (HV/MV) transformers on the other one. The control variables should be the reactive power of the generators and of the available capacitors/coils, the reactive power exchange through the supplying (HV/MV) transformer. The objective function should be:

- *HVG active power loss* — Minimize the sum of power losses in lines, transformers and capacitors:

$$Obj = \min(\Delta P) = \Delta P^L + \Delta P^{Tr} + \Delta P^C \qquad (7)$$

Whereby the objective function is subject of the of the same constraints as described above (3) – (5).

To maintain control of the reactive power flow on the area

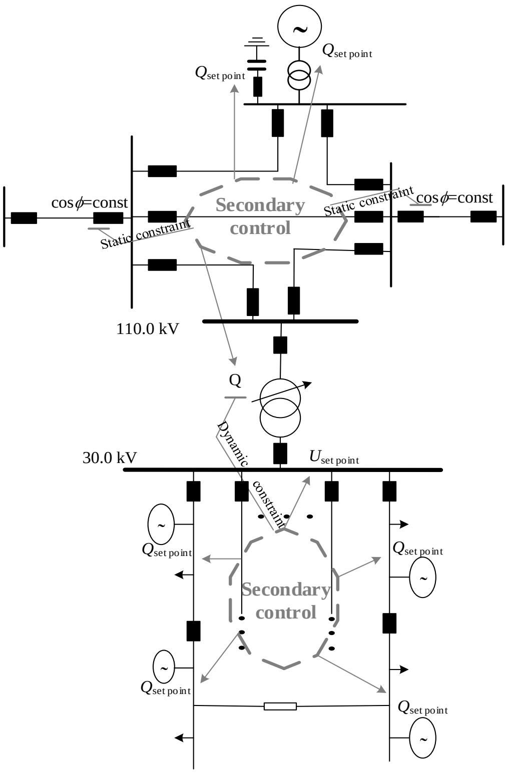

Fig. 8. Control schema for the coordinated operation of the medium and high voltage grid

boundaries the following static constraint should be set

$$\cos\varphi = const. \tag{8}$$

The latter secondary control type operates on the different medium voltage subsystem areas. The operational worthiness of this type of secondary control has been confirmed from the research project ZUQDE. The difference in this case concerns the constraint on the supplying transformer. In this case, dynamic constraints are relevant. The reactive power Q through the supplying transformer or the corresponding $\cos\phi$ is calculated from the HVG secondary control and send as set point to the MVG secondary control. The last one should keep this dynamic constraint until the next value is transmitted. The other way around will also work. Following calculation of the desired Q or $\cos\phi$, the MVG secondary control will send the request to the HVG secondary control. After having checked the request, the operator of the HVG will will approve the new set point.

CONCLUSIONS

The large scale DG integration requires supplementary reactive power resources which create an uncontrolled reactive power flow and therefore cause serious problems on the operation of the HVG. The using of the $Q(U)$ controllers considerably modifies the load vs. voltage static characteristic.

The coordination and the control of the Volt/var in medium and high voltage grid is proposed to be realized by two secondary control loop types for the MVG and HVG respectively. The interaction between the loops is realized by dynamic constraints on the supplying transformer, while the restriction with other HVG utilities is realized by the static constraints on the boundaries. Thus, the reactive power flow and the voltage will be maintained within the predefined limits simultaneously on high and medium voltage grid also in presence of a high DG share.

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