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Identification of Reactive Power Provision Boundaries of a Distribution Grid with DFIGs to a Transmission Grid

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Abstract—Development of the distribution grids brings also new challenges. With efficient exploitation of all the available resources in the grid, many related problems can be solved. The problem addressed in this paper is becoming more and more common in the practice. There is a need to control reactive power exchange between the grids of different voltage levels. This need becomes more pronounced with increasing penetration of distributed generation and cables in the system. But, the cause of the problem can be also a part of its solution. This paper shows that it is possible to control the reactive power exchange to a noticeable extent using the distributed generation located in the grid and the on-load tap changers. The results have been obtained from the analysis of a representative model of Swedish distribution network with installed DFIG wind turbines. While not going deeper into the control strategies, the reactive power boundaries of the system are identified. Critical elements are found for different case scenarios. Solutions on adjustment of reactive power capabilities of the grid are proposed.

Index Terms—DFIG, reactive power provision, radial distribution grid, voltage control, wind power

I. INTRODUCTION

Traditionally, the grids are designed to transfer electrical power from the point of common coupling (PCC) with a transmission network to consumers in the radial grid. With the eminent future increase of penetration of distributed generation (DG), distribution grids will have to change further. Their operation will become more similar to the transmission networks' operation. Besides more complex design, integration of DG can bring more benefits than harms to the system [1]–[3]. Another significant change in the distribution systems is substantial installment of medium voltage cables. As a consequence, distribution system operators (DSO) are recording more frequent inverse reactive power flows towards the transmission network [4]. Both of the mentioned changes are associated with the problem of controlling reactive power exchange at the PCC. This paper addresses it by identifying the overall distribution system reactive power capability.

Currently, many DSOs have regulations from which distributed generation is expected to operate at constant power

factor equal to one [5], [6] thus not providing nor consuming reactive power. This is mainly motivated from maximization of the profit of DSOs which comes from an active power generation and reduction of active power losses. Although, some DSOs require distributed generation to run with power factor slightly lower than one (0.97–0.95, inductive) mainly because of the voltage problems in electrically remote areas of the grid [6], [7]. A number of papers [8]–[15] propose use of the DG to provide reactive power support to a distribution grid and assist in a voltage control and enhancement of electrical power quality. The conclusions are that participation of these sources benefits the distribution grid, allowing better controllability of the voltage profile down the radial feeders.

The papers [8]–[15] are describing different strategies to establish the control of reactive power at the PCC. Depending on the strategy, they require different degree of communication support. Non among these papers is dealing with identification of reactive power control limits at the PCC. This paper is analyzing these further. Identification of the reactive power boundaries could be of the great significance when designing control strategy or planning future investments in the grid. The idea is that the distribution grid can be represented as any other element of the system connected to a transmission grid (ex. generator or motor). Accordingly, reactive power capability of the grid could be defined.

In order to design the full reactive power capability of the grid, all the possible loading situations of the grid would have to be analyzed. This type of analysis goes beyond the scope of this paper. Instead, two utmost cases regarding reactive power exchange at the PCC are analyzed. These cases describe the different nature of active power flows in the grid. The first case that is regarded as utmost is illustrating the state with small production and big consumption. The other one represents big production and small consumption in the grid.

Besides the identification of reactive power boundaries, the limiting factors of the system are also identified. Depending on the constraints that have been hit, it is shown that these factors could be associated to the DG units or the grid itself. If the voltage violation on a bus of the grid occurs, the limiting factors are the active power flows and R/X ratios of

the lines. For the case of violation of reactive power limits of DG, the limiting factors are the DG units themselves. As an independent influence, on-load tap changer (OLTC) participation in the control is considered.

All the analyses have been conducted on the model of a typical Swedish rural distribution grid with installed DFIG wind turbines. It is shown that the limits in which reactive power at the PCC can be controlled are significant. Furthermore, solutions for adjustment of reactive power boundaries have been proposed.

II. PROBLEM FORMULATION

The system that will be analyzed is a typical radial distribution network with distributed wind power and loads. Example of one branch of this system is shown on Fig. 1.

Fig. 1. Example of a radial feeder with distributed generation

Objective of the analysis is to find if the distribution grid is suitable for reactive power support towards transmission grid. As one of the results, it is also important to see what upgrade to the grid could be done in order to improve its reactive support potential. The variable of the biggest importance that is monitored is the reactive power exchange at the PCC. Parameters that might strongly influence reactive power support include:

- length of the feeder sections
- R/X ratio of the feeder sections
- disposition of DG (wind power)
- disposition of loads on the feeder
- bandwidth of the OLTC at the PCC

Beside parameters, the active power flows along the feeder and its influence needs to be considered too. From this point of view, interesting cases are:

- maximum consumption of the system with generation at its minimum
- minimum consumption of the system with generation at 50% of its maximum

These cases are here assumed to be utmost states for analysis of the system according to [16] and are specific for the analyzed grid. The amount of the reactive power support to a transmission grid is bounded by limits of the system including:

- voltage limits on the buses
- current limits on the lines
- reactive power limits of the generating units

Regarding all the above, the problem could be described as a bounded nonlinear, non convex optimization task where the objective function is the function of reactive power output to the PCC (2) with limits on state variables: voltages on the buses and currents on the lines. Reactive power outputs of

generating units as control variables are bounded by reactive power limits which are influenced by a rating of a power electronics equipment S_n and the active power P production of the unit (1). In the case of DFIGs, reactive power limits are very well analyzed in [17], [18]. Generally speaking, DFIGs can absorb more reactive power than they can produce. These abilities depend on the rated stator current, rated rotor current, rated rotor voltage and rated apparent power of a grid side converter. Some of the papers [8], [12] neglect first three limits and only use the last one. In that case, reactive power limits of DFIGs are simply defined by (1).

$$Q_{lim} = \pm \sqrt{S_n^2 - P^2} \quad (1)$$

In the following sections, numerical analysis of the problem is presented as well as the used methodology.

III. METHODOLOGY

The algorithm used for the power flow analysis is based on the customized Newton-Raphson method for having better robustness. All generating nodes are regarded as PV nodes with implemented reactive power limits defined by [17], [18] and (1). In order to maximize the reactive power support at the PCC, an optimization routine is developed. For the purpose of finding the optimal solution, combination of a genetic algorithm [19] and a gradient based optimization method are used. Firstly, the genetic algorithm runs a random search of possible global and local extremums. After running for a number of iterations, it can be expected that its solution converged to a convex area of a search horizon containing also the global extremum. The solution point is then passed to the gradient based optimization method. Solution of this method will converge to the global extremum having in mind that the starting point of its search is in the convex area containing that extremum.

For both optimization routines, common objective (fitness) function to be maximized is used (2):

$$F = A_1(A_{12} + Q_1)^5 - A_2(\sum P_{(i)loss})^5 \quad (2)$$

where $\sum P_{(i)loss}$ is the total active power loss in the system and Q_1 is reactive power provision at the PCC. Coefficients A_1 and A_2 are taking into account the trade off between delivering reactive power to the PCC and decreasing active power losses in the grid which are usually two opposite requests [8]. For the future work, choice of A_1 and A_2 could be optimized according to different criteria: economical, ecological, etc. In this paper, active power losses will be neglected in the objective function by setting $A_2 = 0$.

Coefficients A_1 and A_{12} are set depending if the objective is to maximize provision or consumption of reactive power at the PCC. This has to be done in order to tailor the fitness function [19] depending on the optimization criteria. The same reason is why the elements of (2) are put on power of five. Never mind the case, fitness function always needs to have positive value in order for the algorithm to work. Accordingly, coefficients A_1 and A_{12} respectively take the following values:

- provision: $A_1 = 1$ and $A_{12} = 0$
- consumption: $A_1 = -1$ and $A_{12} = -1.2Q_{max}$ where Q_{max} is the reactive power calculated for the provision case

Controllable reactive power sources are assumed to be all generating units (PV nodes) in the grid. As control inputs to the optimization algorithm, voltage amplitudes of PV buses are used. By properly defining the search horizon, voltage limitations of the controlled buses are satisfied. Reactive power limits of generating units are accounted for in the power flow algorithm described earlier. All the controlled variables should therefore be in the limits defined by physical properties of the system. To make sure that other system buses do not exceed the voltage limits during genetic algorithm iterations, penalizing function is introduced:

$$F(i) = F(i) - \sum_{j=1, \delta U_j > \Delta U}^N \delta U_j C_j, \quad i = 1..M \quad (3)$$

where $\delta U_j = |U_j - U_n|$, U_n is the nominal voltage of the buses in the system, ΔU - maximum allowable absolute voltage deviation, C_j - penalizing factor of each node, N - number of nodes in the system and M - number of chromosomes in a generation of genetic algorithm.

IV. NUMERICAL ANALYSIS

Exchange of reactive power between analyzed grid and a transmission grid depends on a number of parameters as has been stated in section II. In order to analyze their influence, test system represented on Fig. 2 is used. It represents typical Swedish rural 10kV distribution grid. Bus 1 is considered to be a low voltage side of an on-load tap changing transformer. It is also considered as the PCC with a regional subtransmission 70kV network. This grid is assumed to be a strong grid. Distribution grid is assumed to have operating voltage limits of $\Delta U = 0.03$ p.u.

At bus 4 of the grid, there is a small 2MW run-of-the river hydro power plant. This type of hydro power plant does not have any storage reservoir, so it is not able to regulate active power. For the purpose of the analysis in this paper, it will be assumed that for all the cases this power plant runs at 2MW active power with no ability to support reactive power (keeps the unity power factor). DFIG 2MW wind turbines are installed at buses 13, 29, 35 and 41 as can be seen from Fig. 2. They have ability to provide reactive support according to the limits described by (1) and [17], [18]. It is also assumed that the voltage at the PCC is fully controllable by tap changing transformer in the range of voltage limits of the system.

A. System loading influence

The goal of the numerical analysis is to identify upper and lower reactive power support limits of the system at the PCC for different operating conditions:

- case 1: maximum consumption of the system with generation at its minimum

Fig. 2. Typical Swedish 10kV rural distribution grid

case 2: minimum consumption of the system with generation at 50% of its maximum

By running the optimal power flow algorithm described in the section III, reactive power limits of the system are identified. Voltages at buses 1(PCC), 13, 29, 35 and 41 are used as control inputs. Results of the analysis are listed in Table I. Voltage profiles of the system are shown on Fig. 3 and Fig. 4.

From the values in Table I it can be seen that reactive support limits of the system depend highly on the operating state of the system. Active power flows in the system are highly affecting the voltage profile because of the high R/X

TABLE I
REACTIVE POWER EXPORT AT THE PCC FOR DIFFERENT TEST CASES

	case 1	case 2
$Q_{min(PCC)}[p.u.]$	-1.6514	-9.08
$Q_{max(PCC)}[p.u.]$	7.1652	-1.6478

TABLE II
ACTIVE POWER EXPORT AT THE PCC FOR DIFFERENT TEST CASES

Active power exchange	case 1	case 2
$P(Q_{min})[p.u.]$	0.4453	5.2481
$P(Q_{max})[p.u.]$	-0.2815	6.3663

Fig. 3. Voltage profiles of the system for the case 1

Fig. 4. Voltage profiles of the system for the case 2

ratios of the lines ($R/X = (1.2, 1.8)$). This can be seen by comparing the values of reactive power from the Table I with values of active power exchange at the PCC represented in Table II. Positive values of the powers stand for export towards the transmission grid.

If the active power export is high, the reactive power boundaries are shifted towards consumption of reactive power from the grid. This is in accordance with the fact that the reactive power sources start to consume reactive power in order to keep the bus voltages within the limits of the system. For the case when there is a small amount of active power export or the system imports the active power, the situation is different. In this case the system has more space regarding voltage boundaries for provision of reactive power.

B. Influence of reactive power limits of the DG

The system reactive power capabilities are also affected by reactive power limits of the DG. This situation is happening when maximizing the reactive power at the PCC in the case 1 and minimizing it in the case 2. Both cases are represented respectively on the Fig. 3(a) and Fig. 4(b). In the first case,

DG connected to the bus 13 hit the upper reactive power boundary. As a consequence, it was not able to reach the maximum allowable voltage. In the second case, DG at buses 13 and 29 hit lower reactive power boundaries not being able to reach minimum allowable voltage. By reading values of respective reactive powers at the PCC (Table I), it can be seen that these cases are the most extreme ones. The reactive power boundaries are hit when the system state allows utmost reactive power exchange at the PCC.

C. On-load tap changer influence

It has been identified that in general on-load tap changers (OLTC) are the important devices when it comes to voltage control in distribution grids [20], [21]. Therefore, it is very interesting to analyze their influence on the reactive power boundaries of the system. In order to do so, numerical analysis is repeated without the control of the OLTC in point 1 and the results are compared with the ones from Table I.

The same optimal power flow algorithm described in the section III is run on all the cases with the difference that bus 1 is excluded from control inputs. The value of the voltage at

TABLE III
REACTIVE POWER BOUNDARIES OF THE SYSTEM WITH AND WITHOUT THE OLTC

Export powers at the PCC	with OLTC		without OLTC	
	case 1	case 2	case 1	case 2
$Q_{min(PCC)}[p.u]$	-1.6514	-9.08	-0.2347	-8.1830
$Q_{max(PCC)}[p.u]$	7.1652	-1.6478	5.1170	-3.8060
$P(Q_{min})[p.u]$	0.4453	5.2481	0.5647	5.5607
$P(Q_{max})[p.u]$	-0.2815	6.3663	0.0656	6.1091

TABLE IV
INCREASE OF THE REACTIVE BANDWIDTH WITH USE OF THE OLTC

	case 1	case 2
$\Delta(\Delta Q)_{rel}[\%]$	64.74	69.80

the PCC is assumed constant and equal to $U(1) = 1$ p.u. for the purpose of this analysis. The results of active and reactive power exchange at the PCC for the case with the OLTC and without it are presented in Table III.

The influence of the OLTC on the reactive power capability of the grid can be seen by analyzing the values from Table III. If the OLTC is used for voltage control, bandwidth ($\Delta Q = Q_{max(PCC)} - Q_{min(PCC)}$) in which the reactive power exchange can be controlled is significantly increased (Table IV). With the use of the OLTC, the offset (4) from the zero exchange value is somewhat shifted towards the export of the reactive power.

The first implication of using the OLTC regarding ΔQ is generally true for any grid. The second one is specific to the analyzed grid. The offset shift is partially occurring because of the DG installed at the bus 4. This source does not have the ability to support reactive power (operates at unity power factor) and keeps its active power production constant. In order not to jeopardize the voltage limits at bus 4, the OLTC cannot set the maximum possible voltage at the PCC. On the other way, this problem does not exist when the voltage is set to the minimum value. As a result, the OLTC can create more space in the grid regarding voltage limits for reactive power export at the PCC than reactive power import.

V. ADJUSTMENT OF THE BANDWIDTH OFFSET

In section IV-C it has been shown that the offset of reactive bandwidth of the system (ΔQ_{off}) can not be eliminated with the use of the OLTC. On contrary, its use can even increase the offset in certain cases. On the other hand, the OLTC is very beneficial when it comes to increasing reactive bandwidth of the system.

Depending on the needs of a reactive power support of the higher voltage grid, the offset of reactive bandwidth might have to be adjusted. Most common way to do this is to install reactor and capacitor banks at the PCC substation [22]. This solution has been proven in practice and has been in use for quite some time. Recent research is also proposing tap changer staggering techniques for the local control of reactive power at

the PCC [23], [24]. This solution introduces additional reactive power losses in the transformer. Therefore, it can be used only for increase of consumption of reactive power by the distribution grid. The negative side of staggering techniques is that it also introduces additional active power losses in the transformer.

In this section it will be shown how the offset can be eliminated with traditional approach using capacitor and reactor banks. By their installation at the substation, additional admittance is introduced to the bus 1 (PCC). Since the offset is varying depending on the loading of the system, the admittance have to be varied too. In practice, the admittance does not have to be adjusted often. It can be controlled on the hourly basis or even slower. The important part is to determine the range of change of the admittance.

For the purpose of the analysis it will be assumed that conductance of the admittance is negligible. Therefore, only pure susceptance will be calculated. The offset of the reactive bandwidth $\Delta Q_{off}(t)$ in some point of time t can be defined:

$$\Delta Q_{off}(t) = \frac{Q_{min}(t) + Q_{max}(t)}{2} \quad (4)$$

where $Q_{min}(t)$ is lower and $Q_{max}(t)$ is higher reactive limit of the system at the moment t .

Accordingly, minimum and maximum values of susceptance B can be found as:

$$B_{min} = \min \frac{\Delta Q(t)}{U_{PCC}^2(t)}, \quad t = (-\inf, \inf) \quad (5a)$$

$$B_{max} = \max \frac{\Delta Q(t)}{U_{PCC}^2(t)}, \quad t = (-\inf, \inf) \quad (5b)$$

where $U_{PCC}(t)$ is the voltage at the PCC at the time t . In practice, the time interval should be defined according to the available measurement data.

The susceptance should be changed in some time intervals (hours). It is important to define setpoint values of susceptance during these intervals. As a criteria, the offsets during the observed interval should be minimized. According to that, setpoint for susceptance B in time interval $T = (t_0, t_0 + \Delta T)$ can be calculated as:

$$B(t_0) = \frac{1}{2} \frac{\int_{t_0}^{t_0+\Delta T} (Q_{min}(t) + Q_{max}(t))dt}{\int_{t_0}^{t_0+\Delta T} U_{PCC}^2(t)dt} \quad (6)$$

Most of the distribution substations nowadays are already using the capacitor and reactor switching solutions. Therefore, further investments are not needed to implement concept described in this section. Combination of this concept with tap changer staggering technique should provide very efficient way of adjusting the reactive bandwidth offset.

VI. DISCUSSION

This paper presented a method to identify reactive power capabilities of the distribution system as a whole looking from a transmission grid. The analyzed grid can be regarded

as any other element (ex. electrical machine) in a system that exchanges active and reactive power with a network. Therefore, reactive capability curve can be drawn in the same manner as has been drawn for DFIGs in [17], [18]. Most reactive capability curves do not include the influence of the terminal voltage. The same shortcoming is present in this paper since the transmission grid is assumed to be a strong grid. Its influence has to be further investigated.

Due to the lack of measurement data, only two specific, utmost cases were analyzed. In order to identify the full reactive capability of the system, the analysis has to be conducted for a broader range of system loading scenarios.

Demand in the grid has been modeled as a constant power load. The effects of voltage sensitive loads on the reactive capabilities of the grid have to be analyzed in the future.

VII. CONCLUSION

While not going deeper into the control strategies, this paper identifies the reactive power capabilities of the grid. It is shown that the reactive power capability depends highly on the operating state of the system. The first analyzed situation is described by high demand and low generation. For this case the system is more capable of generating reactive power. In the second case with a high generation and low demand the systems capabilities shift towards the consumption of reactive power. This shift is highly pronounced because of the high R/X ratios of the lines in the distribution system.

Reactive power capabilities of certain DFIGs have impact on overall reactive capability of the system in the utmost operating situations in the system. Because of that, they might highly influence the overall high and low reactive power boundary of the system. These situations are illustrated in the paper by maximum reactive export in the case 1 and maximum reactive import in the case 2 of the analyzed grid.

Coordination of the DG and the OLTC in the system has big benefits. With use of the OLTC, reactive bandwidth of the system can be increased for more than 60%. But, while increasing the range it cannot eliminate the problem of reactive bandwidth offset. Therefore, as a solution to mitigate this problem, traditional approach for compensation of reactive power with capacitor/reactor bank system is proposed in this paper. As a supplementary solution, tap-staggering method can be used.

The identification of reactive power boundaries of the system is of the great importance when it comes to designing appropriate control strategy as well as planning the future investments in the grid. Beside identification of reactive capabilities of the grid, the limiting factors are recognized as well. By recognizing the limiting factors, smart investment decision can be made increasing the overall capabilities of the grid and preparing it for the future challenges.

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