Loss-Reduced Reactive Power Control Strategies for Transmission System Support with Renewable Energy Sources

Hartmudt Köppe, Bernd Engel
Technische Universität Braunschweig
Institute for High Voltage Technology and Electrical Power Systems – elenia
Brunswick, Germany
h.koeppe@tu-braunschweig.de

Robin Grab, Sönke Rogalla
Fraunhofer Institute for Solar Energy Systems ISE
Freiburg, Germany
robin.grab@ise.fraunhofer.de

***Abstract*— In times of reduced feed-in from thermal power plants, new reactive power control strategies are needed. In this work, a central reactive power control strategy called DRPC is used to minimize the reactive power flow demand of the distribution system vis-à-vis the transmission system. In a simulation model representing a high voltage grid, the reactive power from local renewable energy power plants is used successfully to compensate the distribution grid's reactive power demand which may cause lower grid losses. However, this increased participation of renewables in grid management leads to higher losses on wind or solar park level. A second simulation model was used to quantify these effects and to demonstrate the feasibility of DRPC with renewable energy sources on park level.**

Keywords- Reactive power, transmission grid, active distribution grid, reactive power management, virtual power plant, park losses

I. INTRODUCTION

Distribution grids are usually characterized as passive networks, with a low active and reactive power feed-in. This role is changing as a result of the drastically increasing share of variable renewable energy power plants (VRE) [1] which are mainly connected on distribution grid level. Consequently, VRE must assume further responsibilities for the reliable operation of the power grid. One of several facets is the provision of reactive power, not just for local voltage levelling, but also for grid-wide balancing. Currently, this task is mainly assumed by large thermal power plants, which operate with an adjustable power factor. As these generators are being replaced by VRE, reactive power for grid-balancing must come from alternative sources. Furthermore, as a result of the fluctuating power feed-in of VRE, the reactive power flow is increasing and more and more variable. The dynamic provision of reactive power is one of the main challenges for the stability of future power grids.

In the absence of large thermal power plants, reactive power can be provided very dynamically by conventional reactive power compensation systems like coils, capacitors, static var compensators or phase shifters. These devices are often used on transmission system level but are not very common in distribution or subtransmission grids [2].

As an alternative, inverter-connected VRE are generally capable of providing reactive power. Since voltage stability is one of the main limitation factors for the integration of VRE, especially in low voltage grids, VRE are typically required to support the voltage by providing reactive power. In low and medium voltage grids the most common approaches are reactive power characteristics like Q(V) and cosφ(P) [2]. In these cases, reactive power from VRE is mainly used for local voltage compensation.

On the contrary, the voltage stability is usually not a limitation factor in high voltage (HV) and ultrahigh voltage (UHV) grids. The main reason is that UHV/HV and HV/MV transformers are able to change the transmission ratio during operation. As a result of that, VRE are able to provide a larger amount of reactive power and contribute to system stability (see TABLE I). The main advantage is the low investment cost. Furthermore, this approach has other advantages as well. VRE are generally connected at distribution grid level. This means that they are able to provide reactive power where it is needed. As a result they can support overlayed or underlayed networks, reduce the loading and increase the transmission capacity.

The topics of this work are the technical aspects of this reactive power management method. A control algorithm is programmed to coordinate the reactive power feed-in of a large amount of VRE with minimal grid losses. Furthermore, in case of wind and photovoltaic (PV) parks connected to the same grid connection point, an additional control is programmed to minimize the losses for the VRE.

TABLE I. REACTIVE POWER SUPPLY MODES AND THEIR PURPOSE

Reactive power supply mode	Intended purpose
Q(V)	Suitable for local voltage balancing
cos φ set-point	
Q set-point	Preferable for HV grid management

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II. FUNDAMENTALS

A. Limitations of Reactive Power Provision from VRE

Presently, the reactive power capability of VRE is usually limited to the requirements set by feed-in guidelines like the German “TAB High Voltage Var. 2” (TAB HV) [3] which defines the requirements for power plants connected to the HV network. It is defined that during times with low or no active power generation, the VRE are not obligated to provide reactive power. Due to the intermittent nature of their energy sources, this is quite frequently the case for wind and PV power plants. Therefore, their usefulness for continuous reactive power provision is generally limited.

However, Power Generating Units (PGUs) such as PV inverters or wind turbines with full power converters have the theoretical potential to provide reactive power up to the amount of their entire rated power to the grid, even in times of zero available primary power [4]. This increases the possibilities of reactive power management with VRE enormously.

If such a PGU fulfills the requirements from TAB HV, it must be capable of providing a reactive power of $Q_{MAX} = 0.411 \cdot P_{NOM}$ without any curtailment. This means that the inverter has to be designed for an apparent power of $S_{MAX} = \sqrt{P_{NOM}{}^2 + Q_{MAX}{}^2} \cong 1.08 \cdot P_{NOM}$. For this study, two scenarios were investigated: Firstly, reactive power limitations as set by TAB HV and BDEW medium voltage guideline (BDEW MVG) [5] were used. Secondly, it was assumed that all VRE are capable of reaching any operation point inside the apparent power semicircle, spanning from 100 % active power production to 100 % phase shifting. Fig. 1 shows the limitations set by TAB HV and BDEW MVG as well as the expanded Q characteristics.

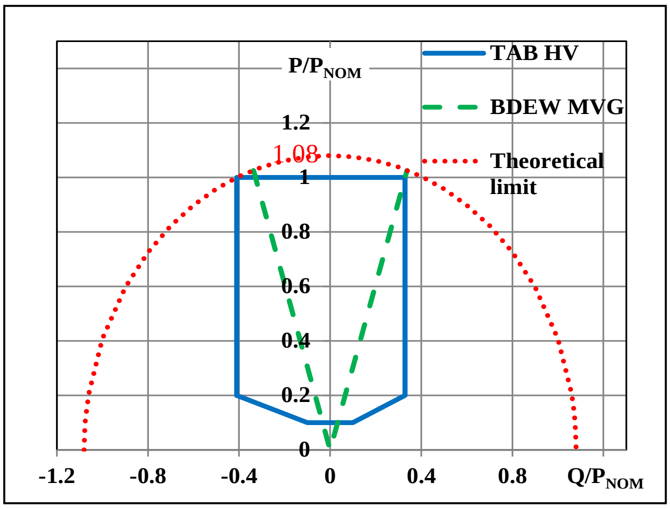

Fig. 1: Reactive power limitations in TAB HV, BDEW MVG, and apparent power semicircle

On grid level, there are other restrictions as well. The voltage level will be influenced due to the reactive power feed-in and may exceed the tolerated range. While the voltage is inside the permitted range, the VRE can provide reactive power as long as other operating equipment is not overloaded as well. Other limitations could be contracts or agreements of the grid participants.

Inside these limitations, VRE are able to provide reactive power dynamically and contribute to the system stability.

B. Reactive Power Control Strategies

The control strategies can be divided into decentral and central approaches. Q(V) and cosφ(P) are typical decentral control strategies. They have the advantage that communication infrastructure is not necessarily needed although the contribution of VRE to grid stability is highly restricted. Central control strategies need a communication infrastructure and a coordinated control algorithm to decide which VRE has to deliver what amount of reactive power. The main advantage is that the VRE can be used very dynamically for grid control purposes. The central approach is further discussed and investigated in this work.

A useful strategy is to achieve a specific reactive power flow at a selectable node in the network [6]. This strategy can be divided into two sub-strategies. The first one is to achieve a reactive power equilibrium in the own network here called Dynamic Reactive Power Compensation (DRPC). The grid operator can use DRPC to ensure a reactive power balance with overlayed or underlayed network operators, for example to reduce their loading and avoid penalty payments. Another strategy is called Dynamic Reactive Power Supply (DRPS) and can be used to support overlayed or underlayed networks with reactive power. This will become more important in the future for times with high feed-in from VRE. At these times, there will be a high demand for reactive power and only a few conventional power plants connected to the grid. This strategy will be investigated in future work while the focus of this study is on the DRPC.

C. Proposed Algorithm

The proposed algorithm is separated into an offline and an online simulation part [6]. During the offline simulation, the network is analyzed, a bus admittance matrix is calculated and several load flow and short circuit simulations are done to prioritize which DER is able to deliver reactive power with minimal grid losses.

During the online simulation, the decision is made what amount of reactive power $Q_{i,t}$ each VRE has to provide to achieve the goal at the reference point. The algorithm is depicted in Fig. 2. TABLE II shows the used variables.

TABLE II. DESCRIPTION OF VARIABLES USED IN FIG. 2

Variable	Description
I, I_{max}	(maximum) number of iterations
i	index number of VRE
t, t_{Start}, t_{Step}	time, start time, timestep
$\lvert Q_{Grid}\rvert$	reactive Power Flow on the main transformer
$\lvert Q_{max}\rvert$	maximum reactive power of the selected VRE i
Q_{Set}	setpoint for the reactive power
Q_{Load}	reactive power of the loads
$Q_{i,t}$	reactive power output of the VRE i at time t
$Q_{Grid,new}$	new residual reactive power flow on the main transformer

First of all, a load flow calculation is done to analyze the given conditions in the network for the specific time step t and to identify whether the network is capacitive or inductive. Depending on the actual network conditions, the generators are configured to approach the reactive power setpoint Q_{Set}. Based on the offline simulation it is decided which VRE is delivering what amount of reactive power for which load.

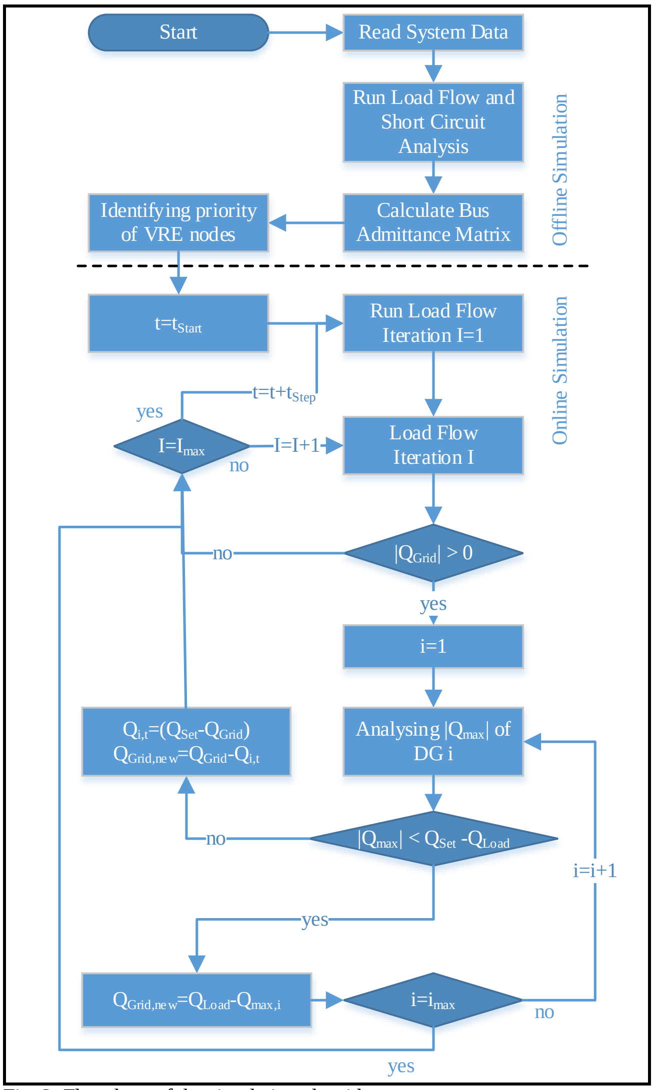

Fig. 2: Flowsheet of the simulation algorithm

If the current generator is not able to deliver enough reactive power, the next generator is considered and so on. After reaching the setpoint, the next time step is calculated. If the VRE are not able to deliver the needed amount of reactive power, the overlayed grid will be used to deliver the deviation. For the simulation and optimization, the power system analysis software PowerFactory is used.

D. Properties of the Test Grid and Profiles

The proposed algorithm is further investigated with a model of a real 110 kV network in Eastern Germany which is depicted in Fig. 3. The reactive power behavior of the grid is mainly influenced by two loads near the UHV/HV transformer: a large town and a large customer. In the area of these loads, there are no VRE connected to the grid which means that the reactive power has to be delivered over a great distance to achieve the goal of reactive power equilibrium in the network.

All loads together consumed about 1400 GWh for the investigated year. At the high voltage level, there are three wind parks with roughly 70 MW installed power and one PV park with about 11 MW. In the underlayed MV networks there are wind parks with 62 MW and PV parks with 86 MW power installed. These VRE produced around 270 GWh. As a result, the network has a VRE penetration level of 20 %. All VRE are used for the control strategy.

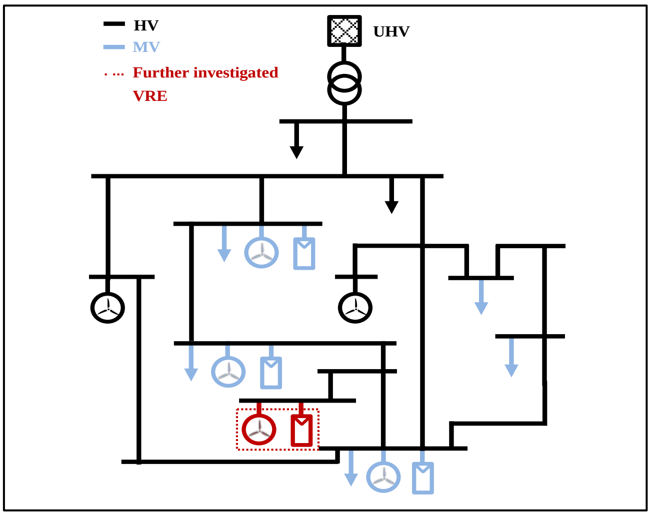

Fig. 3: Topology of the HV model network. Marked VRE is further investigated in Chapter IV

Real measured load and generation profiles are used for the simulation. To reduce the calculation time three typical weeks (winter, spring/autumn, summer) of the year are chosen. In Fig. 4 the typical active power feed-in of wind and PV for the three weeks is depicted.

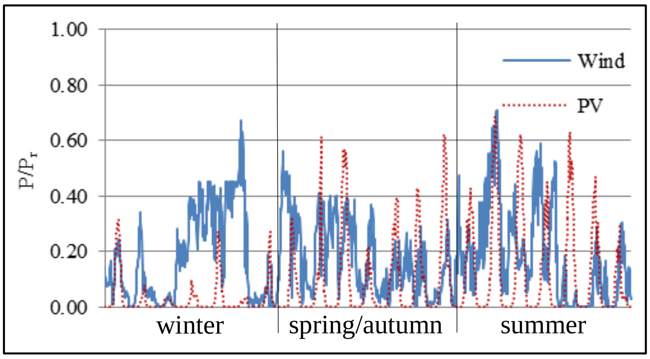

Fig. 4: Ratio of the actual active power feed-in and the rated active power for wind and PV (dotted line)

III. SIMULATION RESULTS ON GRID LEVEL

In this study two cases are distinguished: on the one hand reactive power management within the guideline requirements and on the other hand with the use of the full apparent power semicircle (see Fig. 1). The VRE are controlled with the proposed algorithm to reach a reactive power equilibrium in the own network. Fig. 5 shows the reactive power flow at the main transformer (UHV to HV) with and without the guideline limitations for the simulated winter week in comparison to the case without any optimization.

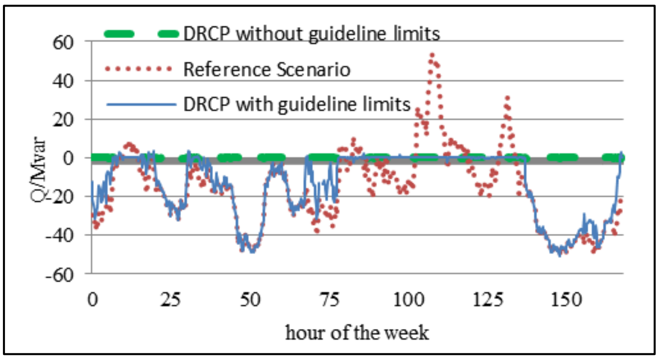

Fig. 5: Reactive power flow at the main transformer for winter

As one can see, without the guideline limitations (dotted line) the reactive power flow can always be kept at the wished setpoint of zero Mvar. This applies to the other simulated weeks as well. The reactive power flow is not exactly zero due to the boundary conditions of the simulation. TABLE III shows the imported reactive energy and the change of the grid losses in comparison to the reference scenario.

TABLE III. IMPORTED AMOUNT OF REACTIVE ENERGY AND TOTAL GRID LOSSES FOR DRPC WITHOUT THE GUIDELINE LIMITATIONS IN COMPARISON TO THE REFERENCE SCENARIO

	Winter	Spring	Summer
$\lvert E_{Q_{Import}} \rvert$ in Mvarh Reference Scenario	6988.24	3259.12	3762.12
$\lvert E_{Q_{Import}} \rvert$ in Mvarh DRPC	6.64	3.12	2.43
ΔP_V (%)	+0.43	+0.18	+0.24

It can be observed that the grid losses are slightly increased. For a reactive power equilibrium, the VRE have to deliver the full amount of reactive power for the grid even for the two loads next to the UHV/HV transformer. As already mentioned this means that the reactive power has to be transmitted over a long distance which causes the higher grid losses. It can be assumed that the losses would be reduced if VRE were connected near these loads.

For the case the power plants are only required to provide reactive power within the guideline limitations, it is harder to reach the setpoint (see Fig. 5, solid line) and most of the time it is not possible. The main reason is that the VRE are only delivering a small amount or no reactive power at times with a low active power feed-in. This is quite often the case for PV systems and for wind turbines as well. Nonetheless, the imported amount of reactive energy can be drastically reduced as TABLE IV shows.

TABLE IV. IMPORTED AMOUNT OF REACTIVE ENERGY AND TOTAL GRID LOSSES FOR DRPC WITH THE GUIDELINE LIMITATIONS IN COMPARISON TO THE REFERENCE SCENARIOS

	Winter	Spring	Summer
$\lvert E_{Q_{Import}} \rvert$ in Mvarh Reference Scenario	6988.24	3259.12	3762.12
$\lvert E_{Q_{Import}} \rvert$ in Mvarh DRPC	2285.66	1312.03	1864.71
ΔP_V (%)	-0.54	-0.61	-0.45

On account of the guideline limitations, the mentioned two large loads at the UHV/HV transformer are regularly supplied by the UHV network. So the VRE are mainly used to compensate the reactive power flow on a local level. Both causes lower currents on grid level which lead to reduced grid losses. However, the losses on park level will increase due to the higher current. This is further investigated in the following chapter.

IV. SIMULATION RESULTS ON POWER PLANT LEVEL

A. Description of the Power Plant Model

As has been demonstrated above, an optimized reactive power management with Q feed-in from VRE can not only be beneficial for general grid management, but even reduce transmission losses within the grid. However, it puts an additional burden on the VRE since an increased amount of reactive power provision from these sources leads to higher currents within the power plants, higher stress for the internal components, and potentially even active power curtailing losses. As has been shown in [7], curtailment losses mainly occur for extreme Q setpoints and can be effectively reduced or avoided altogether when VRE with different primary energy sources such as wind and PV are operated in a synchronized way.

In this work, performance tests as well as cable and transformer loss analyses were carried out with a SIMULINK model of a large VRE located in the same network segment that was used for the grid simulations. The model incorporates a combined power plant consisting of a 10 MW_p PV park and 24 MW of wind turbines. The PV park's power is connected to the park transformer station via two medium voltage lines. The entire VRE is connected to a single point of common coupling (PCC) at the HV level via a 35 MVA transformer. Fig. 6 shows an overview of the combined power plant model. Each PGU was modeled as a controlled current source (Fig. 7). The individual reactive power capacity was either set to TAB HV limitations or, for other simulation scenarios, to the theoretical limit depicted in Fig. 1 with active power priority.

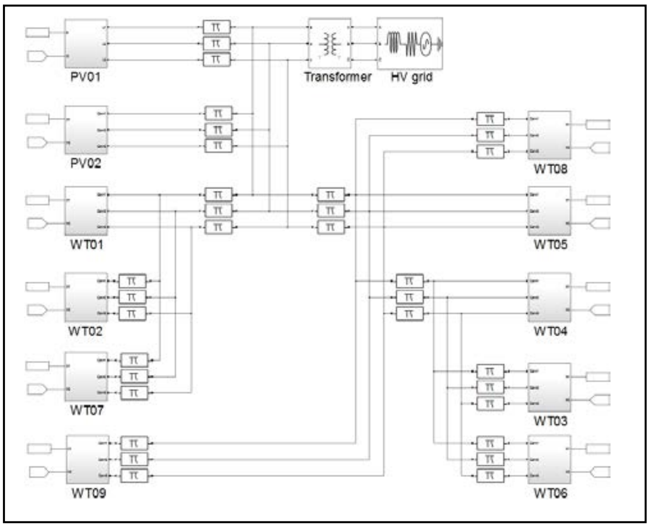

Fig. 6: Overview of the VRE park model

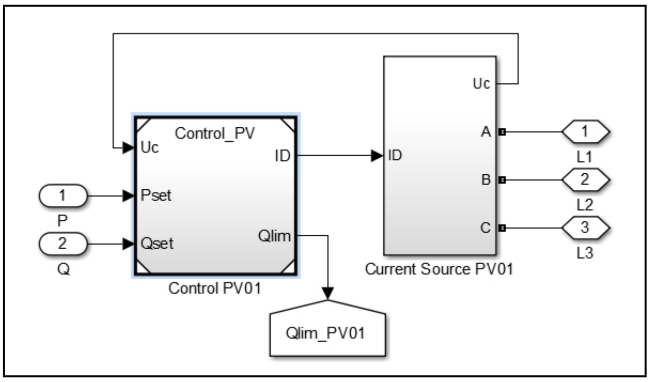

Fig. 7: Modelling of the generators as controlled current sources

B. *Active Power Feed-in and Reactive Power Characteristics*

The VRE model was fed with the same active power input data that was used in the network analysis. Likewise, winter, spring, and summer scenarios were simulated. The park model represents one active node in the network simulation. Accordingly, the optimal Q provision for this node calculated in the network simulation for the DRPC optimization was given as a reactive power profile to the park model (Fig. 8).

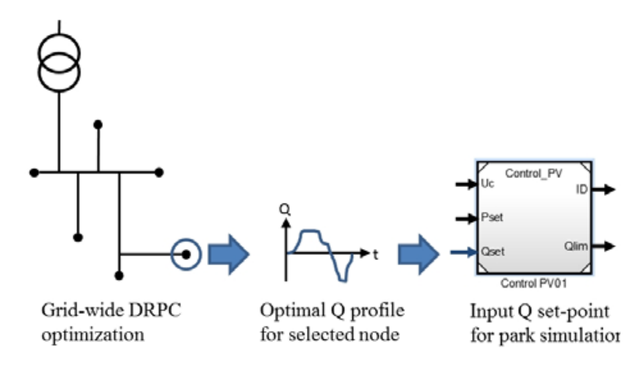

Fig. 8: Input Q profile generation for the park simulations

The considerable grid support that VRE provide in the simulation scenarios without guideline limitations leads to extreme Q setpoints for the nodes. For the "winter" scenario, Q is set to either the overexcited or the underexcited maximum value most of the time. This is especially striking when compared to the reference scenario Qref which consists of real reactive power setpoint curves recorded by the network operator where hardly any reactive power is demanded at all (see Fig. 9).

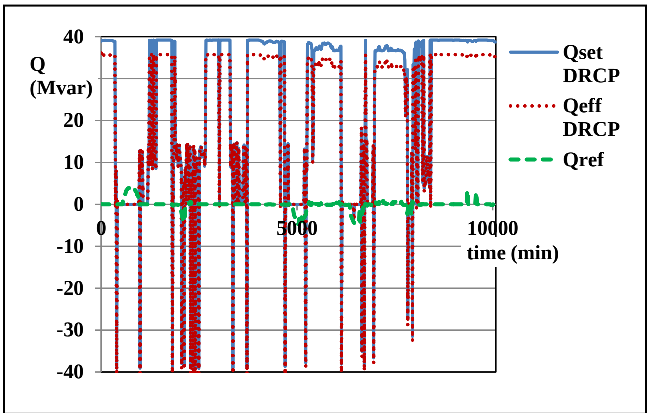

Fig. 9: Q setpoints from DRPC optimization (without guideline limitations) and attained values for VRE model, reference values from actual operation

C. *Fulfillment of Reactive Power Setpoints*

When this setpoint characteristic is given to the park model, the controller tries to distribute the reactive power among the wind turbines and solar park sections so that the set value at the PCC is reached. However, as Fig. **9** demonstrates, very high overexcited setpoints cannot be reached at all with the given VRE. The main reason is that the transformers in the park act as inductive loads, thus effectively offsetting the attainable Q range.

A possible way to evaluate a VRE's capability to fulfill a reactive power demand is the usage of the two characteristic values ***Fulfillment Time*** $\boldsymbol{T_Q}$ and ***Average Deviation*** $\boldsymbol{Q_{DEV}}$ [7] [8]. T_Q designates the percentage of time during which a reactive power setpoint is perfectly met, whereas Q_{DEV} represents the average deviation between the total demanded and supplied reactive power. TABLE V shows T_Q and Q_{DEV} for different simulation scenarios. The grid optimization with DRPC (without guideline limitations) is compared to the reference scenario which has minimal reactive power setpoints.

TABLE V. T_Q AND Q_{DEV} FOR DRPC AND REFERENCE SCENARIOS

	Winter DRPC	Winter Ref.	Summer DRPC	Summer Ref.	Spring DRPC	Spring Ref.
T_Q (%)	34.3	100	75.2	100	72.2	100
Q_{DEV} (kvar)	2088.2	3.2	733.3	1.2	787.3	0.7

For the reference scenarios, the deviation between the setpoint and the resulting reactive power feed-in is neglectable. However, it can be observed that extreme reactive power setpoints as used in the DRPC simulation scenarios will not necessarily be attained by VRE even if the single inverters or wind turbines are configured to provide maximum reactive power support. The reactive power requirements of the park infrastructure such as cables and transformers have to be taken into consideration as well.

D. *Reactive Power Distribution Within the Power Plant*

This effect can be seen more clearly when the reactive power behavior of the park components is depicted separately (Fig. 10). In the studied case, the PGUs give off their maximum overexcited power during times of high demand. However, the HV transformer consumes a considerable amount of this reactive power due to its inductive behavior, thus preventing the power plant from reaching the setpoint at the PCC. In comparison, the cables have very little impact on the reactive power balance in this case.

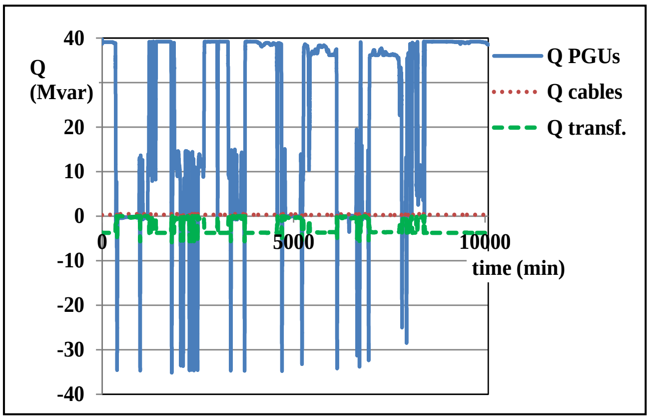

Fig. 10: Reactive power behavior of park components

E. *Energy Losses on Power Plant Level*

High reactive power setpoints close to a VRE's rated power cause high currents within the power plant, which leads to high ohmic losses. In this study, the losses in the HV transformer and in the cables were calculated and put into perspective.

TABLE VI summarizes the losses for the winter, summer, and spring scenarios. The absolute losses in MWh as well as the fraction of the primary energy which is lost are shown. In comparison with the low-reactive power reference scenario, the park losses augmented sharply for the DRPC scenario without guideline limitations, increasing by a factor of five for the winter scenario where the highest feed-in of reactive energy took place. The DRPC scenario where Q limits from TAB HV are observed gives much lower losses which are only slightly increased in comparison with the reference scenario.

TABLE VI. TOTAL PARK LOSSES (CABLE AND TRANSFORMER) FOR DRPC AND REFERENCE SCENARIOS

Absolute and relative park losses	Winter	Summer	Spring
DRPC unlimited	37.0 MWh 4.6 %	18.7 MWh 1.8 %	19.5 MWh 2.1 %
DRPC TAB HV	8.7 MWh 1.1 %	9.9 MWh 1.0 %	8.6 MWh 0.9 %
Reference scenario	7.3 MWh 0.9 %	8.0 MWh 0.8 %	7.0 MWh 0.8 %

Line losses rise proportionally with the square of the current. Consequently, the losses in the park cabling increase massively due to the high currents of the DCRP scenario without guideline limitations. Fig. 11 shows the disproportionate rise of cable losses for the DRPC winter scenario.

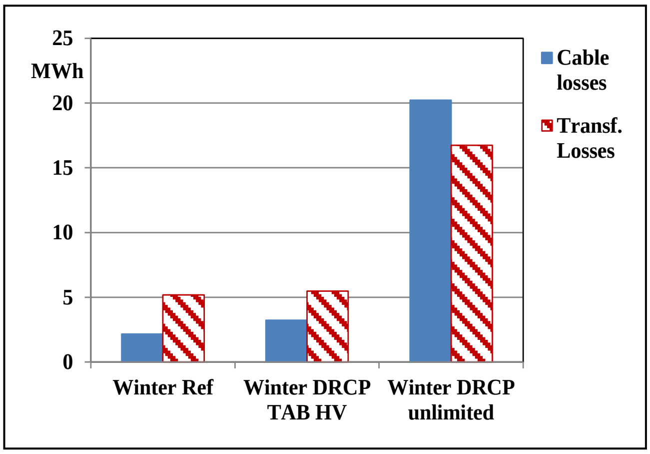

Fig. 11: Cable and transformer losses for the winter scenario

These increased losses are the cost that the DRPC method – which may be very effective on grid level – causes for the power plant. Obviously, these losses are hardly acceptable for an economically viable form of reactive power management. However, the DRPC optimization with TAB HV limits which already gives improved Q balance results on grid level increases the park losses only slightly. It is to be noted that for real-life application of reactive power management, the consequences on park level have to be taken into consideration. Ultimately, it can be necessary to either limit maximum values of reactive power supply from VRE, or sometimes even to redesign the passive components in a renewable power plant so that they perform better in times of high park currents.

V. SUMMARY AND OUTLOOK

An algorithm called DRPC has been developed for a central reactive power management strategy. The goal is to achieve a reactive power equilibrium in the power grid by controlling the reactive power output of distributed VRE. This algorithm has been tested on a model of a real 110 kV network. It was shown that the German guideline limitations are restricting the ability to achieve the equilibrium. However, even under these restrictions, the reactive power import can be reduced drastically which may lead to lower grid losses. Without these limitations, the equilibrium can be reached for every time step. However, the investigated high voltage grid is not optimal for DRPC. Furthermore, every high voltage grid is unique which means that more grids should be investigated in future works. Moreover, the ability of the distribution grid to supply reactive power for the transmission grid should be investigated in future works as well.

Very high reactive power setpoints cannot always be fulfilled by VRE even if the single components offer enough reactive power reserves. The passive equipment such as transformers and cables must be taken into account when the reactive power potential of a VRE is estimated. Moreover, very high reactive power setpoints lead to disproportionally high losses in the passive components, particularly in the cabling. The benefits of advanced reactive power control strategies such as DRPC must be put into perspective with additional losses on generation level. However, the results of the DRPC scenario with guideline limitations show that smaller amounts of reactive power from VRE do not have such a negative effect on the park losses and can already be very advantageous for the grid's reactive power balance. A possible enhancement of this study could be a dynamic setpoint calculation which offers an optimal balance between benefits on grid level and additional losses on power plant level.

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