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Power Loss Reduction in Low-voltage Distribution Grids via Coordinated Reactive Power Management of PV Inverters*

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Abstract. Reducing technical energy losses in the distribution grid has a direct economic benefit for the distribution system operator and furthermore it can increase the grid hosting capacity. Part of the technical losses is due to reactive power in the distribution grid. The approach in this paper is to centrally calculate optimized configurations for local $Q(V)$ control of grid-connected inverters, with the target to reduced technical losses in the low voltage grid. The preliminary assessment in this short paper shows that there is a potential of up to 19.8% loss reduction for a realistic low voltage feeder.

Keywords: Coordinated control · distribution grids · power loss · photovoltaics.

1 Introduction

Due to high resistance-to-reactance ratio and high currents in low voltage distribution grids, the power losses tend to be relatively high compared with the transmission system [11]. Hence, reduction of power losses in the distribution grid is one of the significant issues. Various methods have been proposed to reduce the power losses, e.g., grid topology adjustments [1], capacitor banks [5], and distributed generators [10].

Recently, more and more renewable energy sources (e.g., PV and wind) are integrated into the distribution grids, in particular PV-based distributed generators are installed rapidly to meet the green energy demands in the European

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Union [12]. The evolution of technology of power converters [6–8] provides opportunities to utilize the inverter capabilities to reduce power losses and reduced grid congestion.

In addition, the introduction of communication interfaces to the inverters allows for centralized coordination of inverter settings, such that power losses can be minimized by managing the reactive power of PV systems efficiently, for instance by having the PV systems near the substation produce reactive power to reduce the power flow as well as the power losses in the grid [14,15]. When using Volt-VAR local control, PV inverters near the substation, on the other hand, may be forced to work under unit power factor, since it has a lower sensitivity value than those at the end of the feeder [4]. This means that the reactive power of the PV inverter may be wasted, which could otherwise have been used for, e.g., reducing power losses.

In this paper, a Control Coordination (CC) application of local $Q(V)$ control of PV inverters is proposed with the target to reduced technical losses in the low voltage grid. An objective function focusing on minimization of power losses is designed to generate optimal set-points to those PV inverters.The proposed method is validated in a representative Danish low voltage feeder. The result shows that the proposed CC application has a potential ability to reduce 19.8% power losses.

2 Control Coordination Application and Local Control

The CC application can be designed to maintain voltages within the predefined bound in distribution grid through updating set-points of $Q(V)$ local control of each PV inverter [8]. For the purpose of this paper, a different objective function with the aim of to minimizing the power loss in the distribution grid is introduced and added into the CC application, which calculates the optimal set-points of $Q(V)$ local control of each PV inverter.

2.1 $Q(V)$ Local Control at Inverters

In this paper, $Q(V)$ control shown in Fig. 1(a) is used in each PV inverter as a local controller, which can be formulated such as

$$Q_{PV} = \begin{cases} Q_{\max}, & V_{PV} < V_a \\ \kappa\left(V_{PV} - V_a\right), & V_a \leq V_{PV} \leq V_b \\ 0, & V_b \leq V_{PV} \leq V_c \\ \kappa\left(V_{PV} - V_c\right), & V_c \leq V_{PV} \leq V_d \\ Q_{\min}, & V_{PV} > V_d \end{cases} \quad (1)$$

where $\kappa = \frac{Q_{\max}}{V_a - V_b}\left(V_{PV} - V_a\right)$ represents the droop coefficient. The CC application calculates the optimal set-points of $Q(V)$ to minimize the power losses, and sends them to each PV inverter. Then, $Q(V)$ control in (1) is changed as shown

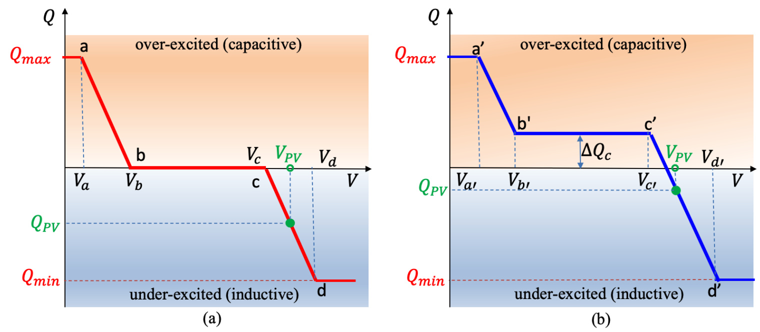

Fig. 1. (a) Default $Q(V)$ control in the PV inverter; (b) $Q(V)$ control corrected by CC application.

in Fig. 1(b). Normally, the voltage at the end of the feeder has an over-voltage issue when the PV system has a peak power, and the voltage near the substation is close the voltage at the substation. Consequently, the PV inverter at the end of the feeder has to operate in the inductive mode to avoid the over-voltage issue, and the PV inverter near the substation can operate in the capacitive mode to minimize the power losses through minimizing reactive power flow in the distribution grid, as shown in Fig. 2.

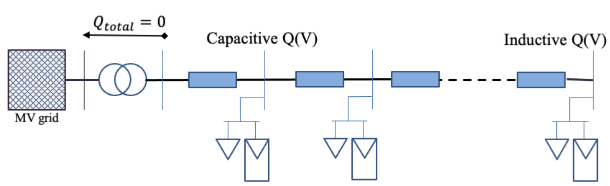

Fig. 2. Loss minimization and voltage reduction in the distribution grid.

2.2 Loss Minimization

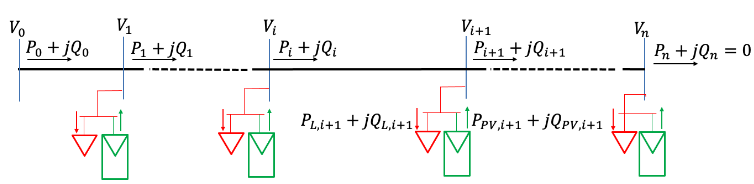

Fig. 3. Power flow in a radial low voltage distribution grid with loads and PVs.

For the sake of the simplicity, we only consider the radial distribution grid segment shown in Fig. 3 in this paper; however, since the layout of this grid section is quite common in low voltage distribution grids, it will serve as a generic example. In the radial distribution grid, the branch flow equations can be formulated as follows [1, 2, 14]:

$$P_{i+1} = P_i - r_i \frac{P_i^2 + Q_i^2}{V_i^2} - P_{L,i+1} + P_{PV,i+1} \tag{2}$$

$$Q_{i+1} = Q_i - x_i \frac{P_i^2 + Q_i^2}{V_i^2} - Q_{L,i+1} + Q_{PV,i+1} \tag{3}$$

$$V_{i+1}^2 = V_i^2 - 2\left(r_i P_i + x_i Q_i\right) + \left(r_i^2 + x_i^2\right) \frac{P_i^2 + Q_i^2}{V_i^2} \tag{4}$$

where P_i and Q_i are the active and reactive power flows and r_i and x_i are the line resistance and reactance from node i to $i+1$, respectively. V_i is the voltage magnitude at node i. Furthermore, $P_{L,i+1}$ and $Q_{L,i+1}$ are the active and reactive power of the load at node $i+1$, and $P_{PV,i+1}$ and $Q_{PV,i+1}$ are the active and reactive power of the PV system at node $i+1$, respectively.

The active power losses in the distribution grid is defined as follow [2]:

$$\mathcal{L}(\mathbf{x}, \mathbf{u}) = \sum_{i=0}^{n-1} r_i \frac{P_i^2 + Q_i^2}{V_i^2}. \tag{5}$$

Minimizing power losses in (5) as much as possible is one of the main targets in the distribution grid. In order to reduce the computational burden of the above optimization, we need a simple version of power flows in (2) to (4) as follows [15]:

$$P_{i+1} = P_i - P_{L,i+1} + P_{PV,i+1} \tag{6}$$

$$Q_{i+1} = Q_i - Q_{L,i+1} + Q_{PV,i+1} \tag{7}$$

$$V_{i+1} = V_i - \frac{(r_i P_i + x_i Q_i)}{V_0} \tag{8}$$

Consequently, the power losses can be simplified as

$$\mathcal{L}(\mathbf{x}, \mathbf{u}) = \sum_{i=0}^{n-1} r_i \frac{P_i^2 + Q_i^2}{V_0^2} \tag{9}$$

The objective of minimization of power losses can be formulated such as

$$\begin{aligned} &\min_{P,Q,P_{PV},Q_{PV},V} \mathcal{L}(\mathbf{x}, \mathbf{u}) \\ &\quad \text{s.t. eqs. (6)-(8).} \end{aligned} \tag{10}$$

In addition, the reactive power capacity of PV inverter should be considered.

$$Q_{PV}^{\min} \leq Q_{PV,i} \leq Q_{PV}^{\max}, \ \forall i. \tag{11}$$

Here, we consider that $\boldsymbol{Q}_{PV}^{\min\,\&\,\max}$ is ± 0.53 pu [8]. From (9), it can be observed that the minimization of power losses is to decrease the reactive power flow since one of the most important targets is extract the active power from PV systems as much as possible. Consequently, the minimization of power losses changes to the following simple form.

$$\begin{aligned} \min_{P,Q,P_{PV},Q_{PV}} \sum_{i=0}^{n-1} r_i \frac{Q_i^2}{V_0^2} \\ \text{s.t. eqs. (6)-(8).} \end{aligned} \tag{12}$$

Thanks to the smart meters deployed in the distribution grid, the CC application can calculate the optimized setpoints and communicate them to the PV inverters see Fig. 4.

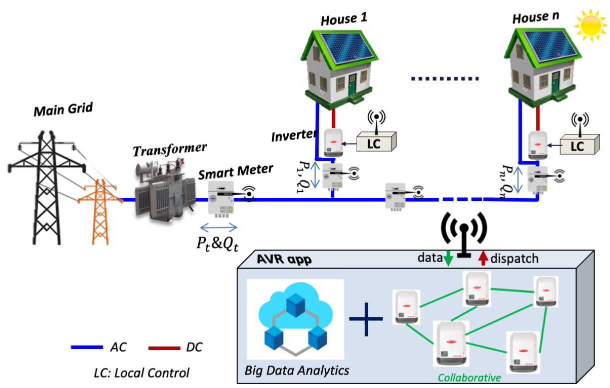

Fig. 4. Control Coordination application implementation in the low voltage distribution grid via communication.

Another target is to maintain the voltage within the limits defined by the grid code [13]. It can be observed from (8) that the voltage magnitude varies based on the active and reactive power flows. E.g., if there exists a reverse active power flow (i.e., $P_{L,i} < P_{PV,i}$), the voltage at the node i is increased. In this case, we can use the reactive power generated by the PV inverter to compensate for that voltage violation. The objective function of voltage violation can be found in [8].

2.3 Flowchart of Control Coordination Application

An overview of the CC application is presented in Fig. 5. At each sample time instant k, the CC application receives all the data including voltage, active power, and reactive power of smart meters and PV inverters via communication. Then,

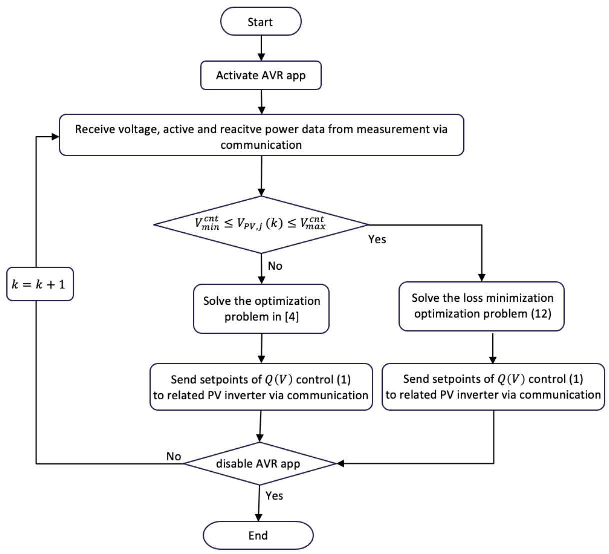

Fig. 5. Flowchart of coordinated control application.

check whether or not the voltage is within the certain bound. If yes, the optimization problem in (9) is solved to obtain optimal set-points of the PV inverters. Then, update $Q(V)$ local control of PV inverter. If no, the optimization problem in [8] is to be solved, and updates the corresponding $Q(V)$ local control of PV inverter. If the CC application continues to optimize the operation of PV inverters, then updates the time instant, i.e., $k + 1$ and continues the first step. Otherwise, the CC application is deactivated.

3 Case Study

In this Section, for the purpose of loss minimization, Feeder 5 of the Danish field trial grid from Net2DG, shown in Fig. 6, is used to test the effectiveness of the CC application. It should be noted that the capacity of the PV inverters is modified compared with the original one. The capacity of each PV inverter is assumed as 5 kVA. The default setting of $Q(V)$ control is $V_a = 0.9$ pu, $V_b = 0.95$ pu, $V_c = 1.05$ pu, $V_d = 1.1$ pu and $Q_a = 0.53$ pu, $Q_{b,c} = 0$ pu, $Q_d = -0.53$ pu [3].

3.1 Loss Minimization

For the sake of the simplicity, a high load operation condition is tested the availability and effectiveness of loss minimization of the CC application, i.e., the power values at the substation are $P = 35.45$ kW & $Q = 25.74$ kVar [9]. Fig. 7 shows that the total power loss within Feeder 5 without the CC application is 0.95 kW. However, when the CC application is activated at 40 s, the total power loss in the grid is decreased to 0.76 kW, which is a 19.8% reduction.

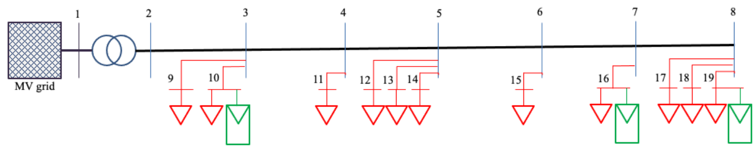

Fig. 6. Feeder 5 of the field trial grid in Denmark [8].

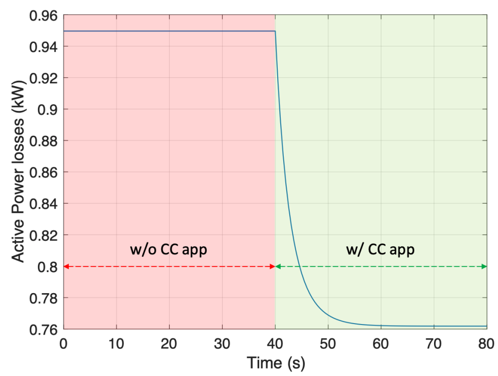

Fig. 7. Loss minimization with and without the CC application.

3.2 Discussion

From the above result, it can be seen that the CC application has the ability to significantly reduce the power loss in the distribution grid. The amount of the loss minimization depends on the capacity of the PV inverters and on the reactive power flows in the distribution grid. For example, when the PV inverters use their maximum reactive power capability to reduce reactive power flow, the power loss is minimized the most by the PV inverters. In addition, managing the active power of PV inverters can reduce the power loss in the grid as well despite reduction of PV owners benefits. However, it can be handled by using energy storage systems to manage the active power efficiently, which leads to keeping local balance, i.e., reducing the active power flow in the grid.

4 Conclusions and Future Works

In this paper, a modified CC application for PV inverters has been presented to not only reduce power losses but also keep the voltages within the certain limit in the low voltage distribution grid. The CC application is designed to manage the reactive power flows efficiently in the low voltage distribution grid in order to reduce the power losses. In the CC application, the optimal set-points of the Volt-VAR local control are calculated centrally for the LV grid area and sent to each PV inverter. The propose method was validated in a Danish representative low voltage distribution grid, in which the proposed CC application can decrease the power losses 19.8%.

In the future works, realistic consumption and generation profiles over longer periods will be used to verify the effectiveness of reduction of power losses via the CC application and additional representative grids with more PV systems will be used to test the proposed method.

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