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Coordinated Control of PV Inverters in Distribution Grid Using Local and Centralized Control*

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Abstract— **A coordinated control strategy of PV inverters is proposed to keep voltages within the specified limits in distribution grids. The proposed method consists of a local volt-VAr control and a centra coordinating control to manage reactive power outputs of PV inverters efficiently. The local control embedded in the inverter controller is operated based on the local measurements in order to improve the voltage quality. The central coordinating control collects measurements throughout the grid to control the voltages inside limits and coordinate the PV inverters' contributions. In the long term, the aim is then to obtain an optimum distribution of their contributions to voltage quality between the different PV inverters. To this purpose, volt-VAr set-points are sent from a central coordinating control to the local one of PV inverters through communication, forcing them to change their reactive power output based on the local measurement voltage and thereby improving the voltage quality. The effectiveness of the proposed method is demonstrated on an actual Danish grid.**

I. Introduction

Due to the rapid development of technology and control of power converters, the more renewable energies can be integrated in to the power grid [1]–[6]. Photovoltaics (PV)-based distributed generation is considered to have an important role to play in meeting the renewable energy demands in many countries [7]. PV provides several technical and environmental advantages, including lower power losses, reduced grid congestion, and low carbon emission, etc. However, with the increasing integration of renewable energy sources into transmission grids or distribution grids as distributed energy resources, the electricity network is starting to face various challenges [8], [9]. One of the most significant of these challenges is voltage violation.

Due to the increasing coupling between the transmission network and distribution network, transmission system operators as well as distribution system operators (DSOs) have to be properly coordinated in order to regulate voltage at both levels effectively. This will be a major challenge as voltage support is required more in the distribution network rather than in the transmission network, while reactive power sources connected to the transmission network will be replaced by distributed generations connected to the distribution network (DN) [10]. DSOs are facing the voltage increase challenge when PV integration into the grid is high [11]. German grid code recommends the PV converters be involved into the voltage support to alleviate their point of coupling's voltage fluctuation in order to connect to the medium-voltage (MV) or low-voltage distribution networks (LVDN) [12], [13].

The voltage quality in the DN can be improved with the proper control strategies of PV systems, which can significantly reduce in the number of utilization of voltage regulating devices [14]. With the development of information and communication technology (ICT), power management strategies in a centralized way are becoming highly efficient at managing distribution energy resources in the DN [15]. In the centralized control, a main controller is normally used to calculate optimal problems considering all relevant constraints based on all the available measurements in the DN. An objective function is formulated to reduce power losses and voltage fluctuations in the DN [16], where an adaptive algorithm is used to select whether the objective function reduces power losses or voltage fluctuations. Compared to conventional methods, the proposed method reduces the need for selection of weighting factors while still obtaining the optimal solution. A dispatch method for PV inverters is designed to minimize power losses in the DN, amounts of curtailed active power, and the deviations of voltage while ensuring voltage regulation [17], where the nonconvex problem is reformulated into a feasible convex one. An additional power balance equality constraint is formulated to consider significant voltage fluctuation and imbalance challenges in the four-wire LVDN [18], where the sequential quadratic programming approach with multiple starting points is used. All the above method will not get the optimization solution when one of the ICT links is failed.

Various reactive power control strategies based on local or global scope, robustness to disturbance, or minimization of violation, are proposed [19]–[21]. The core idea in [19] is to mitigate against voltage magnitude by using reactive power when the short-term PV power fluctuates. However, it is not easy to obtain the optimal solution if the number of buses/PVs is increased in the DN. Recently, a combination of centralized controller and local controller methods have been researched to keep voltages within limits [22], [23]. From the centralized controller, a global optimal problem is solved by all the information measured in the DN and optimal solution is sent to each local controller. In [24], a combination of local and centralized controller is designed to decrease delivery losses based on optimal power flow. A three-level voltage control algorithm consisting of distributed control, droop control, and ramp-rate is designed and validated in the power hardware-in-the-loop system [25]. A local control volt/VAr

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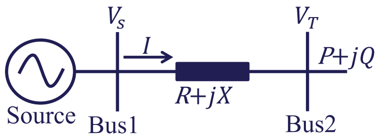


Fig. 1: A simple network structure.

consisting of the negative and zero sequence components of the current is designed to compensate for voltage imbalances in a DN as well as voltage fluctuations [26]. In [27], a method combining volt/VAr and volt/Watt control methods is proposed to keep the voltage variation stay between the results of two methods (volt/VAr and volt/Watt methods). The method thereby exploits the advantages of both volt/VAr and volt/Watt methods without a complex ICT infrastructure.

Motivated by [22], in this paper, a coordinated control strategy of PV inverters is proposed to keep voltages within the specified limits in the LVDN. The proposed method consists of a local volt-VAr control and a centra coordinating control to manage reactive power outputs of PV inverters efficiently. The volt-VAr control strategy is embedded in the inverter local controller, which is operated based on the local measurements in order to improve the voltage quality. The central coordinating control collects measurements throughout the grid in order to control the voltages inside limits and coordinate the PV inverters' contributions based on the voltage sensitivity to the reactive power.. In the long term, the aim is then to obtain an optimum distribution of their contributions to voltage quality among PV inverters in the LVDN. To this purpose, the central coordinating control will send volt-VAr set-points to the local controller of PV inverters through communication, forcing them to change their reactive power output based on the local measurement voltage and thereby improving the voltage quality. The effectiveness of the proposed method is demonstrated on an actual Danish LVDN.

II. Impacts Of Pv Generations In Low Voltage Distribution Network

A serious impediment to integrate higher PV distributed generations is the increased occurrence of voltage rise and bi-directional power flows due to active power injections at the distribution level. These effects can interfere with the operation of tap changers, since the automatic relay voltage reference is no longer indicative of the voltage profile throughout the feeder [28]. This could lead to excessive use of tap changer (hunting effect) that wears the devices and affects severely the voltage stability. The growing use of residential rooftop PVs connected to the LVDN also creates problems, such as various power quality issues.

Generally, PV systems inject their peak power into the LVDN during the middle of the day. However, the load demand in the LVDN is typically lower at this time than the morning/evening consumption peak. In such circumstance of high generation and relatively low consumption, the reverse directional power flow will occur, which brings the aforementioned voltage rise issues. The voltage deviation can be expressed as follows:

$$\begin{aligned}\Delta V = I(R+jX) &= \left(\frac{P+jQ}{V_T}\right)^* (R+jX) \\ &= \frac{PR+QX}{V_T} + j\frac{PX-QR}{V_T}.\end{aligned} \tag{1}$$

where ΔV is the variations of bus voltage, I is the current, V_T is the receiving end voltage, R and X are the line resistance and impedance, respectively, and P and Q are the active and reactive power, respectively. In LV networks, the effect of resistance is no longer negligible due to the higher R/X ratios. Ignoring the imaginary part of (1), $|\Delta V|$ in LV system may be approximated by

$$\Delta V = \frac{PR+QX}{V_T}. \tag{2}$$

The total derivative of $|\Delta V|$ with respect to power transfer is

$$d\Delta V = \frac{R}{V_T}dP + \frac{X}{V_T}dQ. \tag{3}$$

From (8), the voltage magnitude is more sensitive to active power injection than to reactive power due to the high resistance-to-reactance (R/X) ratio in LV systems [29].

A. Voltage Sensitivity

First of all, the power flow P_i and Q_i can be calculated as follows [30]:

$$P_i = |V_i| \sum_{j=1}^{n} |V_j| \, |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j), \tag{4}$$

$$Q_i = -|V_i| \sum_{j=1}^{n} |V_j| \, |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j), \tag{5}$$

where V is the phasor bus voltage, Y is the admittance, θ is the impedance angle, and δ is the voltage angle, In addition, subscript i and j indicate i-th and j-th units. The sensitivity matrix, S, can be calculated by using (4) and (5) as follows [27]:

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = \underbrace{\begin{bmatrix} S_{\theta P} & S_{\theta Q} \\ S_{VP} & S_{VQ} \end{bmatrix}}_{S} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{6}$$

where $S_{\theta P}$ matrix is the impedance angle sensitivity to active power, $S_{\theta Q}$ matrix is the impedance angle sensitivity to reactive power, S_{VP} matrix is the voltage sensitivity to active power, and S_{VQ} matrix is the voltage sensitivity to reactive power. In this paper, we only consider the voltage problem with S_{VP} and S_{VQ}.

B. Reactive Power Control

As introduced before, a candidate method to mitigate the overvoltage problem caused by DGs is the control of reactive power at each inverter [31].

In general, reactive power control methods focusing on 10-min average voltage variations can be divided into four main categories, as follows:

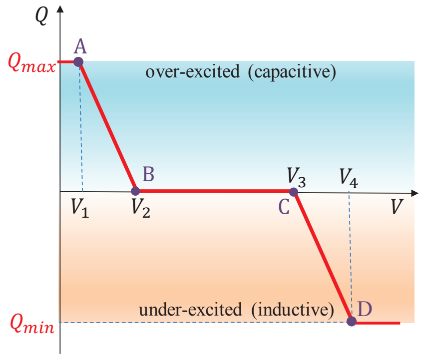


Fig. 2: $Q(V)$ function implemented in PV inverter.

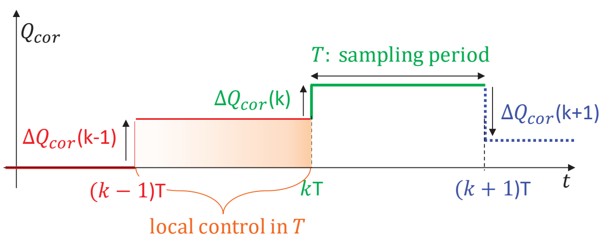


Fig. 3: Sampling time of the coordinated control.

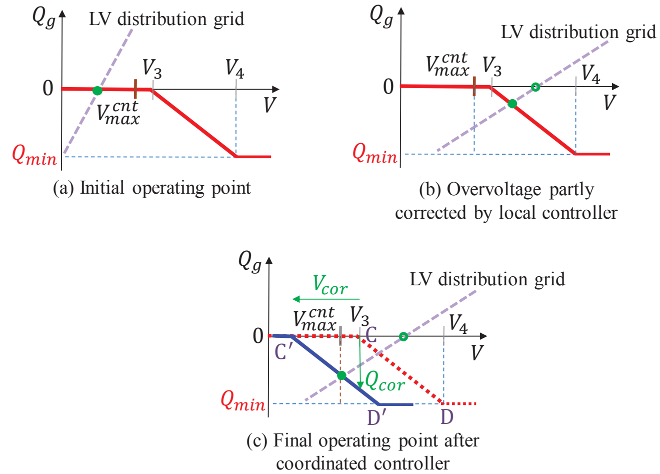
1) Fixed injected reactive power control, e.g., fixed Q or fixed power factor (fixed $\cos\phi$);
2) $Q(V)$ control (reactive power as a function of the local voltage);
3) $\cos\phi(P)$ control (power factor as a function of the active power produced by the PV);
4) $\cos\phi(V)$ control (power factor as a function of the local voltage).

C. $Q(V)$ Control

In this paper, we use $Q(V)$ control method in the local control for each PV inverter. The $Q(V)$ control characteristic is formulated as follows:

$$Q=\begin{cases} Q_{\max}, & V<V_1 \\ \dfrac{Q_{\max}}{V_1-V_2}\left(V-V_1\right), & V_1\leq V\leq V_2 \\ 0, & V_2\leq V\leq V_3 \\ \dfrac{Q_{\min}}{V_4-V_3}\left(V-V_3\right), & V_3\leq V\leq V_4 \\ Q_{\min}, & V>V_4 \end{cases} \qquad (7)$$

where Q is the reactive power, Q_{min} and Q_{max} are the minimum and maximum reactive power generation for the PV inverter, respectively. $V_{1,2,3,4}$ are the voltage levels on which the reactive power outputs. Normally, as shown in Fig. 2 point 'A', if the measured voltage is less than V_1, the PV inverter outputs its maximum reactive power Q_{max}.



(a) Initial operating point

(b) Overvoltage partly corrected by local controller

(c) Final operating point after coordinated controller

Fig. 4: Over-voltage is corrected by the coordinated control [22].

III. Coordinated Centralized Control For Voltage Support

A. Coordinated Control Designed in [22]

At a discrete time k, as shown in Fig. 3, an objective function is formulated to minimize the deviations of the inverter reactive powers, $Q(k+i)$, from their measured values, $Q_m(k)$ over the next N_c steps:

$$\min_{Q,V,\epsilon,\Delta Q}\sum_{j=1}^{n}\sum_{l=1}^{N_c-1}\parallel \alpha_j\Delta Q_j(k+l)\parallel^2+\parallel \beta_j\varepsilon_j\parallel^2 \qquad (8)$$

where $\alpha_j=\sum_{i=1}^{n}S_{VQ,j-i}$, and β is the coefficient of the slack variables.

For i-th PV inverter's voltage, we can approximately calculate it with the sensitively matrix.

$$V_i\left(k+l\right)=V_{m,i}\left(k\right)+\sum_{j=1}^{n}S_{VQ,i-j}\Delta Q_j\left(k+l-1\right) \qquad (9)$$
$$\text{for } \forall l=1,\ldots,n,$$

The following inequality constraints are imposed. The first one is for the slack variables.

$$\varepsilon=[\varepsilon_1,\ldots,\varepsilon_n]\geq 0 \qquad (10)$$

Then, the voltage constraints could be formulated with the limit of the voltage.

$$-\varepsilon_j+V_{\min}^{\text{cut}}\leq \mathbf{V_j}\left(k+l\right)\leq V_{\max}^{\text{cut}}+\varepsilon_j, \qquad (11)$$
$$\text{for } \forall j=1,\ldots,n,$$

Lastly, the output of the reactive power is also constrained by the following equations.

$$\boldsymbol{Q}_{\min}(k)\leq \boldsymbol{Q}_g(k+l)\leq \boldsymbol{Q}_{\max}(k), \qquad (12)$$
$$\Delta\boldsymbol{Q}_g^{\min}\leq \boldsymbol{Q}_g(k+l)-\boldsymbol{Q}_g(k+l-1)\leq \Delta\boldsymbol{Q}_{\max}. \qquad (13)$$

Fig. 4 shows an over-voltage situation and the subsequent actions of the coordinated control to remove the voltage violation. Fig. 4(a) shows an initial operating point of the PV inverter, which is at the intersection of QV characteristics of LVDN and the PV inverter. At this time, the PV inverter is operating at unity power factor. since the voltage lies in the dead-band. Eventually, the LVDN characteristic changes under the effect of a disturbance, which leads the inverter terminal voltage to exceed the upper limit V_3. The green circle shown in Fig. 4(b) is the situation with no control. Then, with the effect of the local controller, the violation is partly corrected as the green dot in Fig. 4(b). However, the voltage still exceeds the upper voltage limit V_{max}^{cnt}, which is set in the coordinated controller. As a consequence, it will compute a sequence of corrections ΔQ_{cor} and send them to the local controller. Finally, the voltage will be shifted as shown in Fig. 4(c) [22].

B. Proposed Coordinated Control

The coordination method designed in [22] corrects the voltage set-points of $Q(V)$ characteristic, as shown in Fig. 5(a). The benefit of this method is that the system will converge to its operating point smoothly within several sampling time. However, the voltage corrected by the other PV inverters has related smaller sensitive values compared with the local reactive power generation of their own PV inverter [27]. In piratical system, the coordination control will use 10 minutes sample time, since smart meters will send measurement every 10 minutes. If we still use such method for the coordination manner, then the system is hardly reach its operating point when the PV irradiance varies.

Consequently, we consider an additional variable, Q_c, to shift down the dead-band of $Q(V)$ characteristic, as shown in Fig. 5(b).

$$\min_{Q,V,\epsilon,\Delta Q,\Delta Q_c} \sum_{j=1}^{n} \sum_{l=1}^{N_c-1} \left[\| \alpha_j \Delta Q_j(k+l) \|^2 + \| \gamma_j \Delta Q_{c,j}(k+l) \|^2\right] + \| \beta_j \varepsilon_j \|^2 \quad (14)$$

The voltage constraint of the proposed method is modified as follows:

$$V_i\,(k+l) = V_{m,i}\,(k) + \sum_{j=1,j\neq i}^{n} S_{VQ,i-j} \Delta Q_{c,j}\,(k+l-1) + S_{VQ,i-i} \Delta Q_i\,(k+l-1)] , \quad \text{for } \forall i = 1, \ldots n. \quad (15)$$

The output of the reactive power for all the PV inverters is also constrained by the following equations.

$$Q_{\min}(k) \leq Q_{g,i}(k+l) \leq Q_{\max}(k), \quad (16)$$

$$\Delta Q_{\min} \leq Q_{g,i}(k+l) - Q_{g,i}(k+l-1) \leq \Delta Q_{\max}. \quad (17)$$

where

$$Q_{g,i}(k+l) = Q_g(k+l-1) + \Delta Q_{c,i}\,(k+l-1) + \Delta Q_i\,(k+l-1) \quad (18)$$

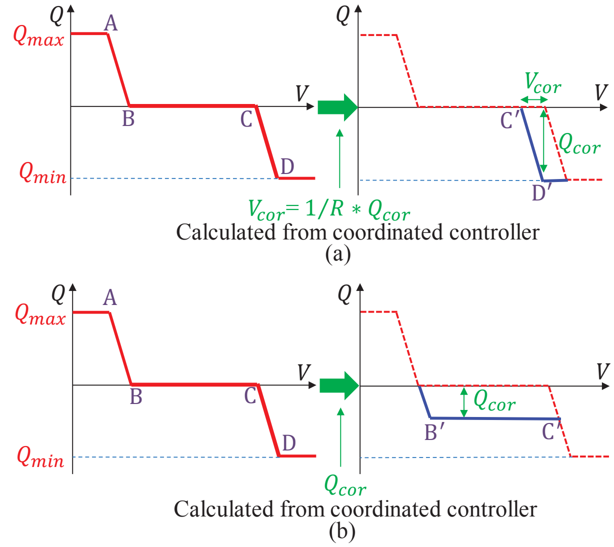


Fig. 5: Modified $Q(V)$ control characteristic. (a) Corrected by V_{cor}; (b) Corrected by Q_{cor}.

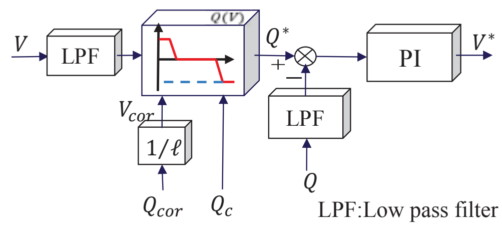


Fig. 6: Block diagram of the coordinated control with the local control.

The coordination control calculates the optimal set points to each local controller at each sampling instance, kT, based on the measurements obtained from the field, as shown in Fig. 3. For example, since the voltage is averaged every 10 minutes, the coordination control loop will also be executed and signals sent to each PV system every 10 minutes. The local control will receive a correction to the reactive power and calculate its new Q(V) control characteristic.

IV. Simulation Results

Fig. 7 shows a reference LVDN model, which is based on an actual grid belonging to Thy-Mors Energi in Denmark [32]. The radial branch highlighted with the red circle, which is compound by six busbars with eleven loads and three PV generation units, was selected for the analysis. In this case, we set $V_{1,2,3,4}$ as 0.9 pu, 0.95 pu, 1.05 pu, and 1.1 pu, respectively. In addition, $Q_{\max} = -Q_{\min} = 0.53$ pu. For the sake of simplicity to verify the proposed coordinated centralized control strategy, it is assumed that the PV inverters generate their maximum active power as a constant and the sampling time of the coordinated control is set to 20 seconds as same as in [22]..

At first, the PV inverters at bus 16 and 19 generate reactive power to support the voltage by their own local

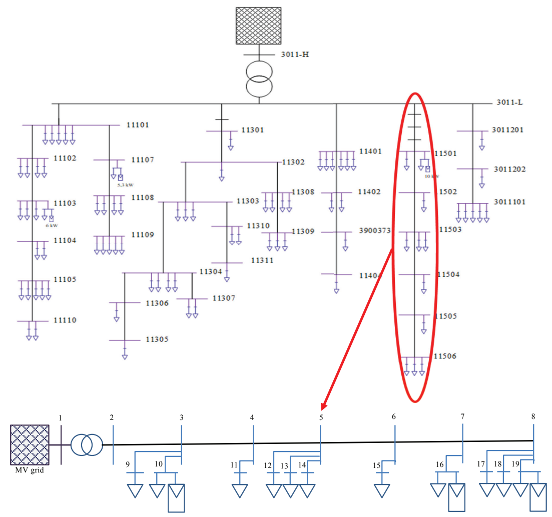


Fig. 7: Reference low voltage distribution network model.

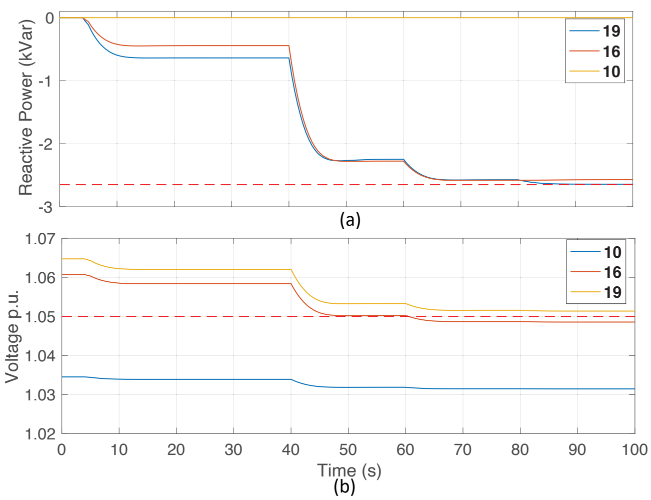


Fig. 8: Simulation results of centralized control without coordination. (a) Reactive power output. (b) Voltages at each PV inverter.

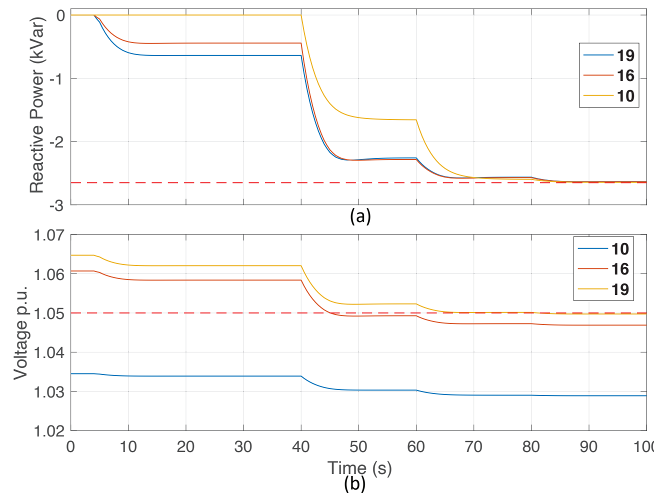


Fig. 9: Simulation results of coordinated control with V_{cor}. (a) Reactive power output. (b) Voltages at each PV inverter.

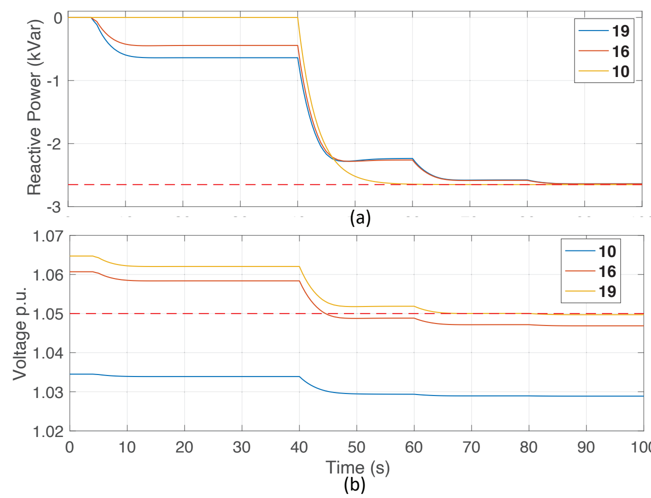


Fig. 10: Simulation results of coordinated control with V_{cor} and Q_{cor}. (a) Reactive power output. (b) Voltages at each PV inverter.

controller, since the voltages is lager than 1.05 pu, which is set as V_{max}^{cut}. At 40 s, the centralized controller is activated and starts to send the corrections to the local control of each PV inverter. Fig. 8 shows the performance without the coordination control. With this method, the PV inverter at bus 10 generates no reactive power since its voltage is always in the bound. However, the voltage at 19 is larger than 1.05 pu after all the PV inverters reach their operating points, as shown in Fig. 8(b). Fig. 9 shows the performance of the coordinated control method designed in [22]. It can be observed that the PV inverter at bus 10 starts to generate the reactive power after receiving the correction from the centralized controller. Fig. 10 shows the performance of the proposed centralized control. It can be observed that the PV inverter at bus 10 generates its maximum reactive power. Fig. 11 shows the total reactive power generation of the PV inverters for compensating voltage rise issues. It can be seen that no coordination method generate less reactive power, but the voltage at 19 is larger than 1.05 pu. Compared with the method in [22], the proposed method makes the system converge its operating point faster.

V. Conclusions

A coordinated control strategy of PV inverters was designed to keep voltages within the specified limits in LVDN. It consists of a local volt-VAr and a central coordinating control of reactive power outputs of PV inverters. The local volt-VAr control embedded in the inverter controller operates in a real-time manner based on the local measurements in order to improve the voltage quality. The central coordinating

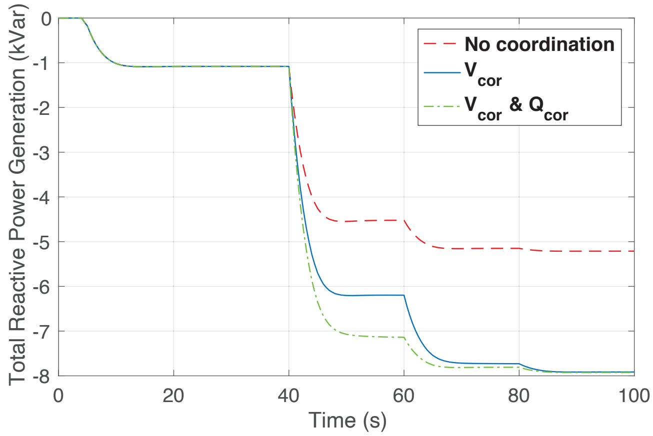


Fig. 11: Total reactive power generation with three methods.

control collects measurements throughout the grid to control the voltages inside limits and coordinate the PV inverters' contributions. In the long term, the aim is then to obtain an optimum distribution of their contributions to voltage quality between the different PV inverters. To this purpose, volt-VAr set-points are sent from a central coordinating control to PV inverters along the feeder, forcing them to change their reactive power output to the local grid and thereby improving the voltage quality. The effectiveness of the proposed method is demonstrated on an actual Danish LVDN.

In the future work, the proposed coordinating control will send its command every 10-15 min based on the 10-15 min average voltage and reactive power values from smart meters.

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