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Reactive power control strategies for renewable energy integration in MV network

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Abstract

The paper presents a comparative study of the potential of four reactive power management of distributed generators (DGs) for overvoltage mitigation in distribution networks. We compare a global optimisation strategy (representing a centralised reactive power management) with local reactive power management solutions. Based on the productible energy level, each strategy is assessed from a criterion of curtailed energy.

1. Introduction

The structure and management of the electricity grid are set to change as a result of the energy transition. The key factors contributing to this evolution are the significant and planned development of decentralized renewable energy generation. In the particular case of rural distribution networks with long feeders and low demand, voltage rise issues will happen with a significant deployment of distributed generation. The aim is to study how reactive power management from electronic power converters (PV inverters) could help for overvoltage mitigation in medium voltage network. The study was carried out with a French DSO who provided information of the network to be studied and data about PV energy generation in the same area. Previous studies have been carried out in [1] where they investigate a local voltage control strategy in active distribution networks. Also in [2], [3] they evaluate combined local and centralised voltage control strategy with respect to network characteristics.

If we consider the radial network in Figure 1 without the DG, power flows from the source substation with voltage U_1 to the downstream nodes U_2 and U_3 . There is a voltage drop from the MV busbar in the substation to the downstream nodes, with risk of violation of the lower limit. This voltage drop is proportional to the line impedance along the feeder. Conventionally, on distribution networks, on-load tap changers are used to maintain the voltage over the whole network within the admissible limits, i.e. $\pm 5\%$ of the nominal voltage for MV and $\pm 10\%$ for LV networks. Due to the increasing integration of decentralized generation on medium- and low-voltage distribution networks, power flows are no longer unidirectional from the substation to the downstream feeders but can also be bidirectional. For a

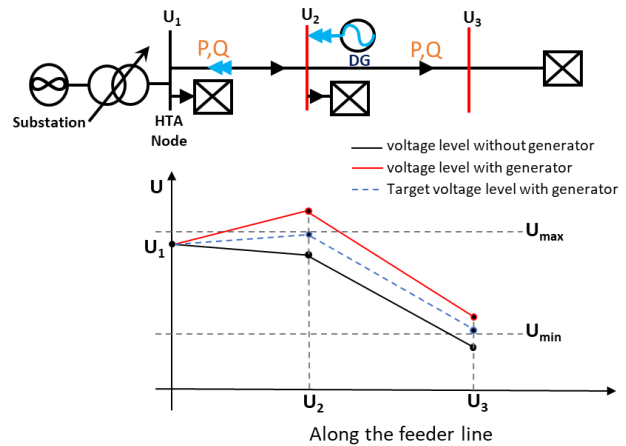


Figure 1: Voltage level for feeder with and without producer

generator installed at node 2, if the demand is low, a part of the generated power will be fed to the substation. The voltage level no longer decreases uniformly, and there is a risk that the voltage limits on the network are violated. The connection solutions offered by DSOs are designed to meet certain obligations [4] such as voltage limits imposed to the network during normal operations. As renewable energy sources (RES) are mainly connected through inverters, the converters can be used to respect voltage limits by modulating reactive power at their point of connection (POC). A reactive power management must be defined for each generation facility.

2. Description of the network under study

Here we present a detailed overview of the real network used for our study. An understanding of the structure and characteristics of this network is necessary to properly

Table 1: Elements of the studied network

ELEMENTS	NUMBER
MV and LV nodes	377
MV nodes	302
LV connected nodes	75
MV and LV producers	16
Lines	200

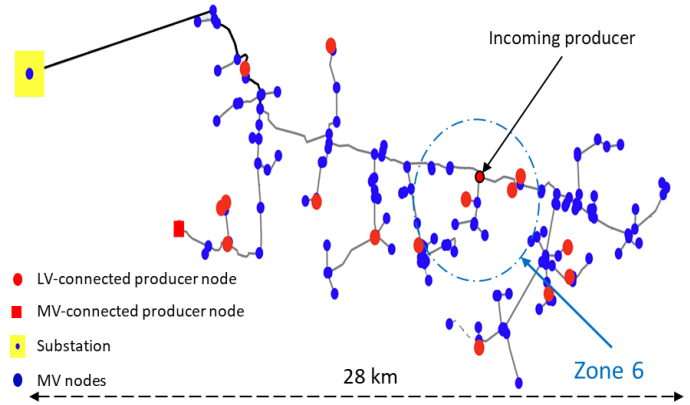


Figure 2: Network with location of new producers

contextualize the results of our analysis. The network consists of a MV feeder with 377 nodes, corresponding to MV and MV/LV substations. It extends for 20 km between the source substation and the furthest node. The cumulative length of the lines on the entire network is 85 km. Figure 2 shows the network structure, with the primary substation shown in yellow. The 75 loads connected to the network represent a variety of demands spread across the entire network. At the same time, the 16 producers supplying energy to the network add a dynamic component, with variations in production depending on the install capacity of each and with respect to producible energy from solar irradiation as obtained from measured data provided by DSO (see section 4). The cumulative capacity of the producers installed on the feeder is 4.9 MW (sum of the total capacity of the 16 generators). The peak load demand of the feeder is 5.8 MW which corresponds to the sum of all consumer subscribed demand.

3. NETWORK SENSITIVITY ANALYSIS

Here we evaluate the network sensitivity to active and reactive power flows to determine the best connection node for a new producer [5], [6]. We first need to calculate the sensitivity coefficients for each node of the network with regard to active power injection and reactive power absorption. From Figure 3a, we express the voltage variation due to active and reactive power injection as follows, neglecting line losses (active and reactive).

$$V_1^2 - V_2^2 \approx -2(RP_2 + XQ_2) \quad (1)$$

This shows that for an injection of active power ($P_2 > 0$ positive for injections) at zero reactive power ($Q_2 = 0$),

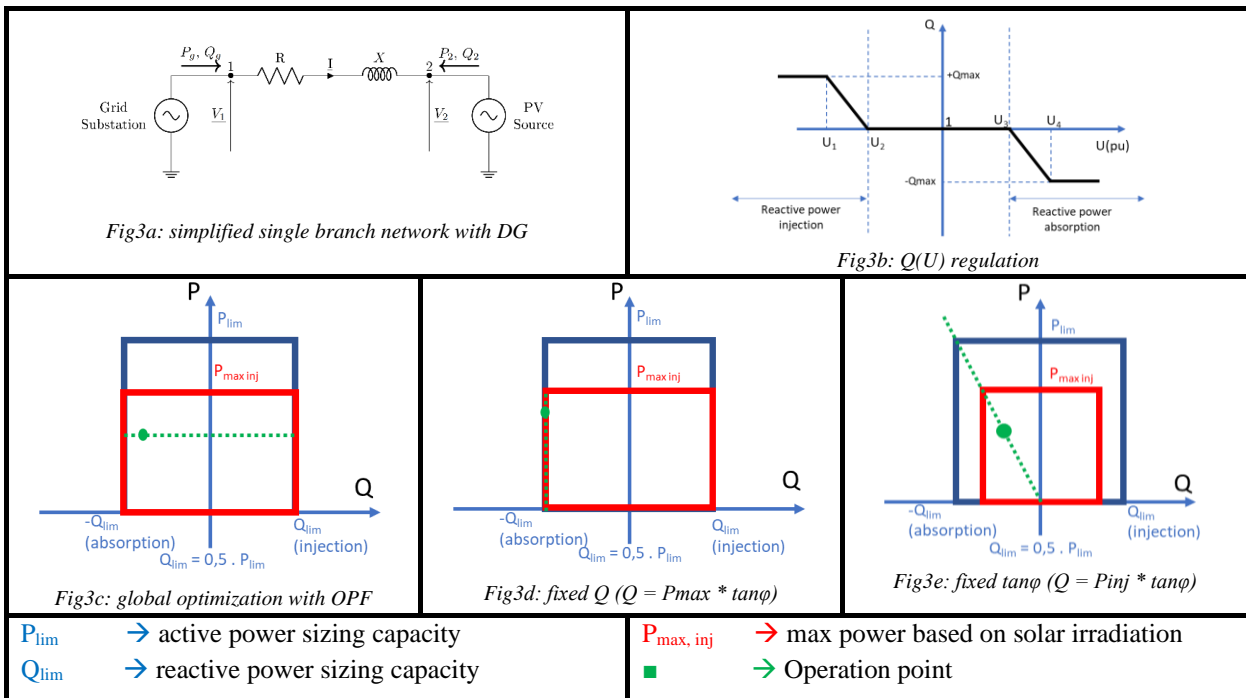


Figure 3: Reactive power control strategies implemented with producer

we have $V_2 > V_1$. To reduce this voltage rise, we need to compensate the effect of P_2 by an action of opposite sign on Q_2 , i.e. a withdrawal of reactive power. Concerning sensitivity coefficients, if we consider a small variation in reactive power at node 2 such that:

$$\begin{cases} Q_2 \rightarrow Q_2 + \Delta Q_2 \\ V_2 \rightarrow V_2' = V_2 + \Delta V_2 \end{cases} \quad (2)$$

and with no change in active power, then $V_2'^2 - V_2^2$ at node 2 depends only on the line reactance and the voltage variation can be expressed as follows:

$$\Delta V_2 = X \cdot \frac{\Delta Q_2}{\left(\frac{V_2' + V_2}{2}\right)} \quad (3)$$

If $\Delta Q_2 > 0$, a small injection of reactive power (or a smaller withdrawal) causes the voltage to rise by an amount $\Delta V_2 > 0$. If we consider that voltage levels remain close to the rated value, then we can write:

$$\frac{(V_2' + V_2)}{2} \approx V_{rated} = 1 \text{ p.u.} \quad (4)$$

The sensitivity coefficient between ΔV_j and ΔQ_j is related to the sum of all reactances X_k of branches k from the substation to the node j on which sensitivity is to be determined.

$$s_{Qj} = \frac{\Delta V_j}{\Delta Q_j} = \left(\sum_{k \in \Omega_j} \frac{X_k}{V_{rated}} \right) \quad (5)$$

$\Omega_j = \{\text{set of branches from substation to node } j\}$

The sensitivity with respect to active power is define similarly using the same approach. Voltage sensitivities to active and reactive power injections/withdrawals depend on the R and X characteristics of the network, and more specifically on the R/X ratio as indicated by the sensitivity ratio:

$$\frac{s_{Pj}}{s_{Qj}} = \frac{\sum R_k}{\sum X_k} \Big|_{k \in \Omega_j} \quad (6)$$

This ratio is highly dependent on the nature of the line sections (overhead or underground) and the conductor/cable cross-sections. The lower the ratio at a network node, the greater the impact of reactive power compared to active power.

4. CONTROL STRATEGIES FOR HTA-CONNECTED GENERATORS

This section explains how to implement and evaluate the four reactive power control strategies on a producer to maximize active power injection (limiting curtailment) while respecting network voltage constraints. From the sensitivity analyses of the network, we determined node 138 in a zone[8], [9] as the optimal point of connection of an incoming producer (producer 17) as shown in Figure 2 The calculation of power injections/absorptions on the network is carried out using the functions of the Pandapower tool scripted in python. We

consider P_{lim} of 1 MW and a $\tan \phi$ of - 0.5, which is the maximum contractual limit as the size of the producer. Load and production data at 10-minute intervals over 1 year (2022) was provided by the DSO.

a) Global optimization:

The optimal power flow (OPF) formulation maximizes the energy injected into the grid by a generator, while limiting the reactive power withdrawn by the same generator. Figure 3c shows the operating point for a producer's at a given level of producible power. Production and consumption levels are defined from 10min curves supplied by the DSO. For each time step point, we define $P_{maxinj} < P_{lim}$ as the producible power. We define the costs functions associated with injecting active power and absorbing reactive power.

$$f_P(P) = C_{2P}P^2 + C_{1P}P + C_{0P} \quad (7)$$

$$f_Q(Q) = C_{2Q}Q^2 + C_{1Q}Q + C_{0Q} \quad (8)$$

We consider only a linear cost for active power ($C_{2P} = 0$ and $C_{1P} < 0$). The reactive power cost function is quadratic ($C_{2Q} > 0$) in order to penalize both large injection and absorbing exchanges. Overall, the OPF calculation minimizes the following sum:

$$\min \sum f_P(P) + f_Q(Q) \quad (9)$$

Figure 4 shows the active power injected and reactive power withdrawn for all generation points, as well as curtailment in relation to the producible power and the voltage levels.

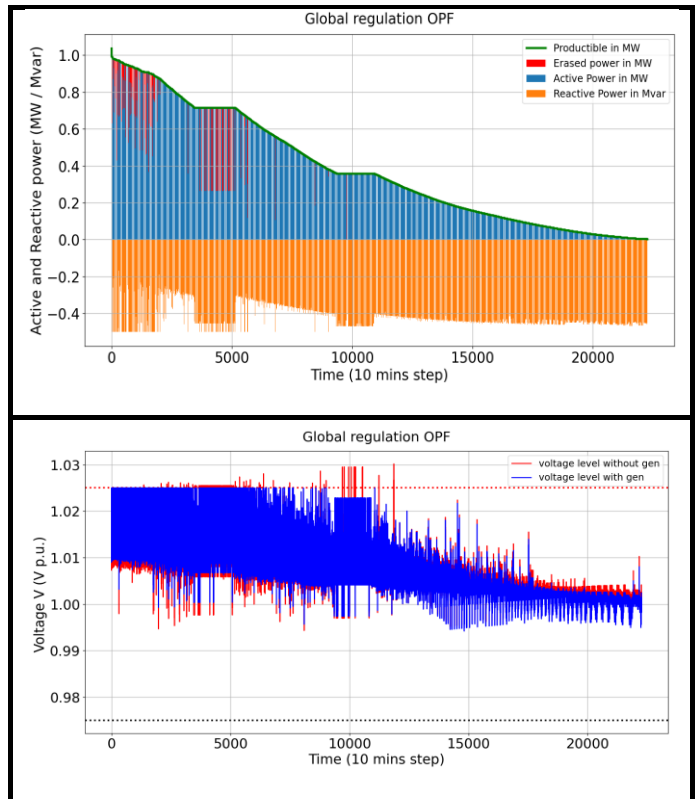


Figure 4: Active and reactive power levels and, network voltage level for global optimisation strategy

b) Fixed Q control:

For this control strategy, whatever the level of active power injected into the network by the generator (depending on producible power from solar irradiation), the reactive power withdrawn from the network remains unchanged and is determined by the fixed value previously set.

$$Q_{sout} = \tan \varphi * P_{lim} = -Q_{lim} \quad (10)$$

c) Fixed tangent φ

For this reactive power control strategy, the ratio between the reactive energy withdrawn (Q) and the active energy (P) injected at the POC of the generating facility is constant. For instance with high production, active power is curtailed until this ratio is reached, in order to respect the set voltage limits on the network.

$$\tan(\varphi) = \frac{Q}{P} = \text{contant} \quad (11)$$

d) Local regulation $Q = f(U)$

The reactive power of the producer varies as a function of the voltage measured at POC (Fig.3b). The challenge is to set the points U_3 and U_4 . We are setting them through running power flow simulations with the producer as P-V node, and we are looking at the maximum voltage variation on the network, as well as the voltage variation at the producer node. Keeping in mind that POC is not necessarily the highest point on the network, as there are "hidden" producers on LV networks.

5. RESULTS

Figure 5 shows the results of the study for each steering law studied. Annual energy production of the new producer is estimated at **1409 MWh** for an installed capacity of 1 MWc. It shows annual curtailment, producer power electronics losses, and additional network losses with the presence of the new producer. It can be observed that the curtailed energy is the highest with "tan φ fixed". From the producer, the curtailed energy must be seen with the impact of converter losses: thus, "global OPF" and "Q(U) law" have similar results. But "Global OPF" seems better for the DSO (less additional losses).

6. CONCLUSION

In this paper four architectures have been outlined for voltage control of medium-voltage distribution networks by a producer. The fixed-Q control law performs similarly to the global optimization in terms of erased energy, but with higher grid and generator losses due to maximum reactive power absorbing. Q(U) regulation is positioned as an intermediate alternative in terms of the compromise between load shedding and generator losses. This regulation law is defined in such a way that the producer only corrects the overvoltage created only by itself. The fixed tan φ control law, generating a higher level of load shedding, with this solution the producer is greatly limited from an energy point of view.

However, it is important to note that such management remains dependent on network configuration, particularly in rural areas where R/X ratio of overhead lines is usually high (≈ 2) and combined with a low consumption density; the effectiveness of these solutions remains very limited.

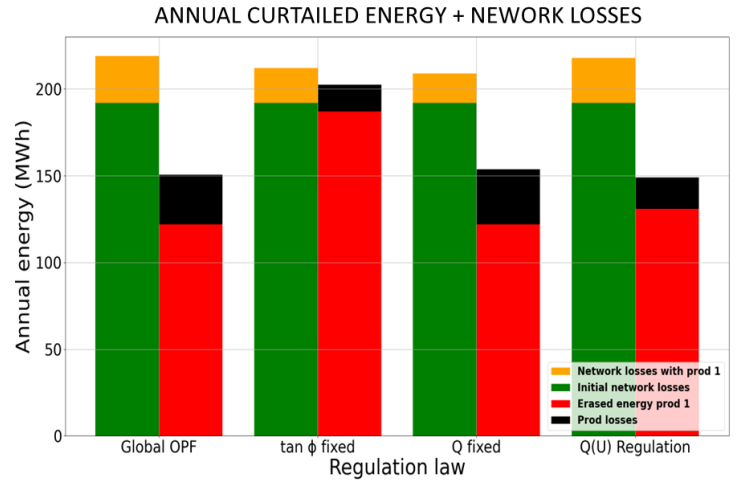


Figure 5: Level of curtailment and losses for each control strategy

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