EVALUATION OF DIFFERENT LOCAL VAR CONTROL STRATEGIES IN LOW VOLTAGE GRIDS

Daniel-Leon SCHULTIS
TU Wien – Austria
daniel-leon.schultis@tuwien.ac.at

Albana ILO
TU Wien – Austria
albana.ilo@tuwien.ac.at

Christian SCHIRMER
TU Wien – Austria
christian.schirmer@tuwien.ac.at

ABSTRACT

This paper compares for the first time the impact of different var-control strategies on the behaviour of low voltage grids. Besides existing control strategies like Q(U)- and cosφ(P)-control of PV-inverters also the new ones, namely L(U)-control with or without Q-Autarkic customers, are investigated. The assessment of different control strategies is made by means of social and technical criteria. Investigations show that involving the prosumer-owned inverters in voltage control entails in principle social issues like discrimination and threat to data privacy. Local cosφ(P)- and Q(U)-control cause relatively high grid losses, extensive Q-exchanges between medium and low voltage grids and thus also considerable distribution transformer loadings. The application of L(U)-control mitigates the social issues and fulfils best the technical criteria. In this case the network operator is able to perform an effective voltage control by using his own devices. This control strategy enables the prosumers to internally compensate their reactive power needs; thus acting Q-Autarkic.

INTRODUCTION

The increasing penetration of photovoltaic (PV) facilities in low voltage (LV) grids is challenging the traditional power system operation; the simultaneous PV-injections cause reverse active power flows which provoke violations of the upper voltage limit and increased equipment loadings and electric losses [1]. However, European distribution system operators (DSOs) have to ensure the compliance of their grid voltages with the EN 50160 limits of ±10% around rated voltage. An option for DSOs to mitigate the rise in voltage is to manipulate the reactive power flows within their grids, for instance by controlling the Q-provision of PV-inverters [2, 3] which are owned by prosumers or by installing and operating own Q-devices for voltage control. Such control concepts strongly impact the Q-balance of distribution grids and lead to uncontrolled Q-flows between different voltage levels [4]. Several control strategies for PV-inverters evolved over the past decade; their capabilities to produce reactive power is used for voltage control in LV-grids. Two established approaches are the $Q(U)$- or $\cos\varphi(P)$-control [2]. Another control strategy for smart inverters is proposed in [5], where they are controlled to supply the reactive power which is needed by the loads in customer plant level at all times. To control grid voltages in case of such Q-Autarkic prosumers, variable shunt-coils with local $L(U)$-control are located at the ends of the violated feeders [5].

This paper evaluates for the first time different var-control strategies used in LV grids by means of social and technical criteria. Firstly, the theoretical test system is described. Secondly, relevant simulation scenarios are defined. In the following the evaluation criteria are defined. Finally, the assessment results are presented.

TEST SYSTEMS DESCRIPTION

This section gives a short description of the test LV-grid, the thereto connected prosumers and the considered var-controls.

Low voltage grid

Fig. 1 shows the theoretical test-grid which is used for the simulations.

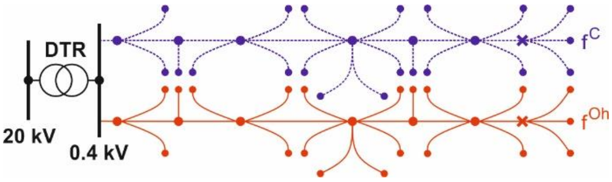

Figure 1: Theoretical test-grid

It consists of two identical feeders: f^C with a cable structure and f^{Oh} with an overhead-line structure, which are connected to the MV-grid through a 20 kV / 0.4 kV, 160 kVA distribution transformer (DTR). Each feeder supplies 20 identical residential prosumers.

Prosumers

Fig. 2 shows the prosumer structure. It is characterized by the active P^{load} and reactive power consumption Q^{load} of his internal loads and the active P^{inv} and reactive power injection Q^{inv} of his PV-system. Voltage dependency of loads is modelled with an inherent ZIP model from [6]; an initial power factor of 0.95 is set for all loads. Each PV-system includes a PV-module with a rating of $\mathrm{P_r^{PV}} = 4\ kWp$ and an inverter with a rating of $\mathrm{S_r^{inv}} = \mathrm{P_r^{PV}}/0.9$. Power losses within PV-systems are neglected. Their reactive power injection is determined by the applied control strategy. If no-control is exercised, inverters inject by power factor one.

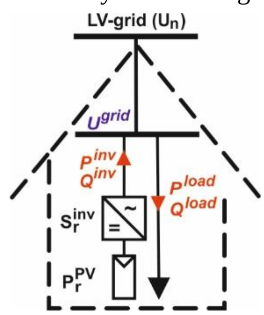

Figure 2: Structure of a prosumer

Control strategies

Simulations are separately performed for local cos$\varphi(P)$-, $Q(U)$- and $L(U)$-control. The latter one is performed also in combination with Q-Autarkic prosumers.

Local cos$\varphi(P)$-control

The power factor $cos\varphi^{inv}$ of a cos$\varphi(P)$-controlled inverter is a function of its actual normalized active power production, $p^{PV} = P^{inv}/P_r^{PV}$. Fig. 3a) shows the simulated cos$\varphi(P)$-characteristic, which is suggested by the Austrian grid code [7].

Local $Q(U)$-control

The normalized reactive power provision $q^{inv} = Q^{inv}/S_r^{inv}$ of a $Q(U)$-controlled inverter is a function of the grid-voltage at its terminal, $u^{grid} = U^{grid}/U_n$, where U_n is the nominal grid voltage. Fig. 3b) shows the simulated $Q(U)$-characteristic; it is based on [8].

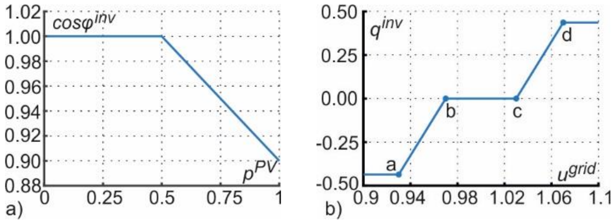

Figure 3: Simulated characteristics of different inverter controls: a) cos$\varphi(P)$-control; b) $Q(U)$-control

Table 1 shows the simulated parameters of $Q(U)$-control.

Table 1: Simulated parameters of $Q(U)$-control

	a	b	c	d
q^{inv}	-0.436	0	0	0.436
u^{grid}	0.93	0.97	1.03	1.07

Local $L(U)$-control

In case of local $L(U)$-control, a sufficiently dimensioned variable shunt-coil with a voltage set-point at 1.09 p.u. is located close to the end of each feeder. The exact location of both coils is marked by crosses "x" in fig. 1. For high feeder-voltages, the coils absorb the amount of reactive power which is required to prevent an exceedance of the defined set-point.

Q-Autarky

The inverters of Q-Autarkic prosumers produce in real time the reactive power which is required by their internal loads. In this case, prosumers absorb and inject active power by power factor one.

SCENARIO DEFINITION

The PV-systems of all prosumers produce the same active power P^{PV} and the same initial consumption value P_{init}^{load} is set for their loads. Four combinations of minimum and maximum values for load and production are simulated, each in presence of either no-, cos$\varphi(P)$-, $Q(U)$-, $L(U)$- or $L(U)$-control combined with Q-Autarkic prosumers. Table 2 shows the assumed P-values for load and production.

Table 2: Simulated P-values for load and production of prosumers

scenario	*ID*	P_{init}^{load} [kW]	P^{inv} [kW]
min load / max prod	1	0.684	4
min load / min prod	2	0.684	0
max load / max prod	3	1.368	4
max load / min prod	4	1.368	0

The slack node is located at the DTR primary side and set with a constant voltage of 1.03 p.u..

EVALUATION CRITERIA

The control strategies are compared to each other with regard to social and technical criteria.

Social criteria

As social criteria are used discrimination of prosumers and threat to their data privacy.

Discrimination: The procurement of non-frequency ancillary services by DSOs should be transparent, non-discriminatory and market based [9]. In a non-discriminatory market, the applied control strategy should enable all prosumers an equal and fair prospect to provide ancillary services to the DSOs.

Data privacy: A coordinated control approach requires data exchanges between the control devices, i.e. inverters and shunt-coils, and a controller. To preserve the data privacy of prosumers, the applied control strategy should allow a coordination of the underlying control devices without requiring any data exchanges between DSOs and prosumers.

Technical criteria

As technical criteria are used the impact on grid voltage, Q-exchange, DTR loading and grid losses. The **impact on grid voltages** is discussed on the basis of the resulting voltage profiles. The **Q-exchange** Q^{ex} between MV- and LV-grid, the **DTR loading** *DTRL*, and the **grid loss** ΔP are direct output of the load flow simulations. Q^{ex} corresponds to the Q-flow at the DTR primary side; grid loss includes active power losses of feeders and DTR.

EVALUATION OF VAR CONTROLS

Following sections discuss and compare the assessment criteria for different control strategies.

Social criteria

In both cases, cos$\varphi(P)$- and $Q(U)$-control, the prosumer-owned PV-inverters are utilized by the DSO for ancillary service procurement. In case of cos$\varphi(P)$-control, assuming equal weather conditions within one LV-grid, all prosumers provide the same amount of normalized reactive power $q^{inv} = Q^{inv}/S_r^{inv}$. In contrast, with $Q(U)$-control, the q-provision of each inverter depends on its local voltage and thus on its location within the LV-grid. Therefore, the use of $Q(U)$ in itself contains the prosumer discrimination, while the cos$\varphi(P)$-control does not. If

$L(U)$-control is applied, whether or not prosumers act Q-Autarkic, prosumers are not requested to provide any ancillary services for voltage control and thus they are not discriminated in principle.
Fig. 4 shows the data flows which are required to perform Q-Autarky and to coordinate the control devices, i.e. PV-inverters or shunt-coils.

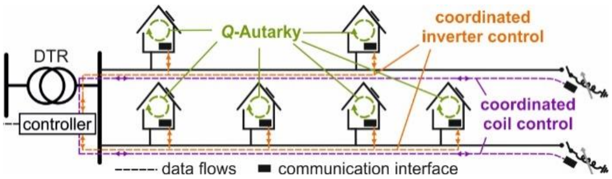

Figure 4: Data flows required to perform Q-Autarky and to coordinate the PV-inverters or shunt-coils

To coordinate PV-inverters for ancillary service procurement and technical issues, the DSO needs to exchange electrical data with the prosumers and thus jeopardizes their data privacy. In contrast, for the shunt-coils' coordination, the DSO needs to exchange data only between its own devices, but not with prosumers. Q-Autarkic prosumers do not need to exchange any data with the DSO.

Technical criteria

Fig. 5a) shows the **voltage profiles** of both test-feeders with no-control for minimal load and maximal production. Both feeders, but especially the overhead feeder, exceed the upper voltage limit. Fig. 5b) shows the voltage profiles of both test-feeders with no control for maximal load and minimal production. No feeder deceeds the lower voltage limit of 0.90 p.u..

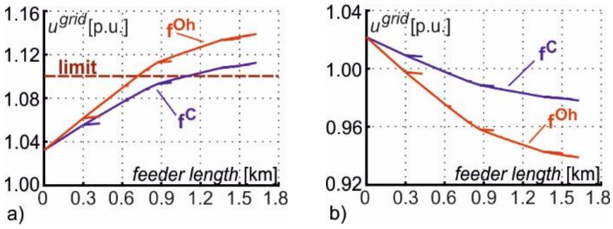
Figure 5: Voltage profiles of both test-feeders with no control for different load-/production-scenarios: a) min load / max production; b) max load / min production

Fig. 6 shows the voltage profiles of both test-feeders for minimal load and maximal production with different control strategies. All var-controls eliminate the violations of the upper voltage limit. Fig. 6a) and 6b) show the profiles with $\cos\varphi(P)$- and $Q(U)$-control, respectively. Both control strategies have a particularly strong impact on the voltage-profile of the overhead line feeder, f^{Oh}; its voltage is decreased more than required to eliminate limit violations, especially in case of $\cos\varphi(P)$-control. Fig. 6c) and 6d) show the profiles with $L(U)$-control and its combination with Q-Autarky, respectively. Both control strategies prevent upper limit violations but do not over-decrease the grid voltages. The feeder voltages are slightly higher in case of Q-Autarkic prosumers.

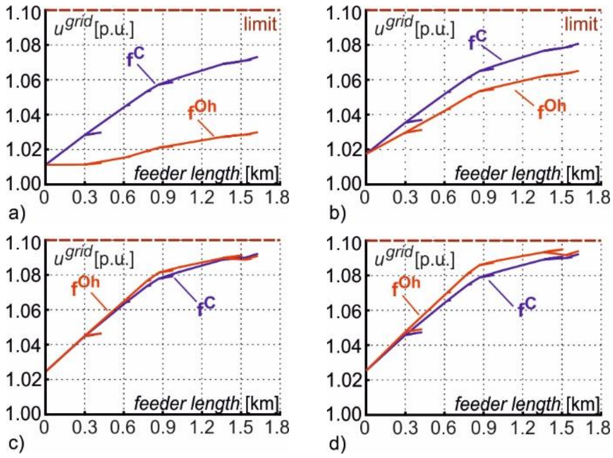
Figure 6: Voltage profiles of both test-feeders for min load / max production with different control strategies: a) $\cos\varphi(P)$; b) $Q(U)$; c) $L(U)$; d) $L(U)$ and Q-Autarky

Fig. 7 shows the ***Q*-exchange** for different load and production scenarios and control strategies. For maximal

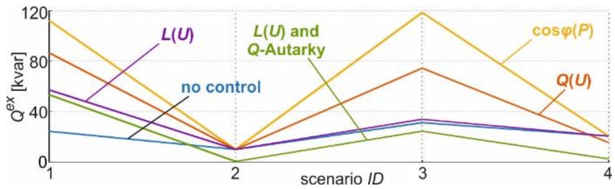

Figure 7: Q-exchange for different load-/production-scenarios and control strategies

PV-production, $Q(U)$- and especially $\cos\varphi(P)$-control lead to excessive Q-flows and thus to high **DTR loadings** and **grid losses**. For maximal load and minimal production, the capacitive behaviour of $Q(U)$-controlled inverters slightly reduces the Q-flows. $L(U)$-control provokes less additional Q-flows, DTR loadings and losses for maximal PV-production. Its combination with Q-Autarkic prosumers eliminates the Q-flows which are not required for voltage control almost completely.

Comparison of control strategies

To gain a comparative overview of the investigated var-controls, the simulation results, i.e. the calculated Q-exchange, DTR loading and grid loss, are summarized according to the following procedure. At first, for each control strategy c, they are added up for all scenarios s, which are defined in table 2, as follows:

$$Q_{\Sigma,c}^{ex} = \sum_{\forall s} Q_{c,s}^{ex} \tag{1}$$

where:
$Q_{c,s}^{ex}$ – Q-exchange for control c and scenario s
$Q_{\Sigma,c}^{ex}$ – accumulated Q-exchange for control c

$$DTRL_{\Sigma,c} = \sum_{\forall s} DTRL_{c,s} \tag{2}$$

where:
$DTRL_{c,s}$ – DTR loading for control c and scenario s
$DTRL_{\Sigma,c}$ – accumulated DTR loading for control c

$$\Delta P_{\Sigma,c} = \sum_{\forall s} \Delta P_{c,s} \tag{3}$$

where:
$\Delta P_{c,s}$ – grid losses for control c and scenario s
$\Delta P_{\Sigma,c}$ – accumulated grid losses for control c

Afterwards, the resulting values are normalized as follows:

$$q_{\Sigma,c}^{ex} = Q_{\Sigma,c}^{ex} / \max_c(Q_{\Sigma,c}^{ex}) \quad (4)$$

where:
$q_{\Sigma,c}^{ex}$ – normalized accum. Q-exchange for control c

$$dtrl_{\Sigma,c} = DTRL_{\Sigma,c} / \max_c(DTRL_{\Sigma,c}) \quad (5)$$

where:
$dtrl_{\Sigma,c}$ – normalized accum. DTR loading for control c

$$\Delta p_{\Sigma,c} = \Delta P_{\Sigma,c} / \max_c(\Delta P_{\Sigma,c}) \quad (6)$$

where:
$\Delta p_{\Sigma,c}$ – normalized accum. grid losses for control c

The calculated values lie in between 0 and 1 and are proportional to the average Q-exchange, DTR loading and grid loss, respectively; they are used for the technical assessment of the control strategies. The social criteria are assessed by a value of either 0 (positive assessment) or 1 (negative assessment). Fig. 8 shows the assessments of the considered social and technical criteria for each control strategy in a spider chart.

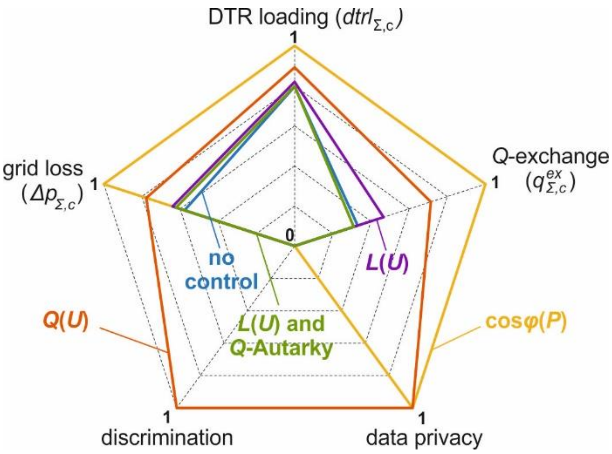

Figure 8: Spider chart of the investigated var-controls

In this chart, a small area indicates a good performance. cosφ(P)-control provokes the highest Q-exchange, DTR loading and grid loss in average; the DSO requires access to electrical data of prosumers for a coordinated var-control and all prosumers have the same prospect to offer ancillary services to the DSO. The application of Q(U)-control improves all technical criteria compared to cosφ(P)-control, but in return, prosumers are discriminated. L(U)-control further reduces undesired Q-exchanges and mitigates the social issues; no access to electrical data of prosumers is required by DSOs for a coordinated var-control and prosumers are not discriminated. Its combination with Q-Autarkic prosumers eliminates Q-flows that are provoked by customer loads, thus reducing the Q-exchange, DTR loading and grid loss, in average.

CONCLUSION

Local Q(U)- and cosφ(P)-control of PV-inverters entail social issues; for a coordinated var-control, the DSOs require access to personal electrical data of prosumers. In case of local Q(U)-control, prosumers do not have a fair and equal prospect to offer ancillary services to the DSOs. Q(U)- and especially cosφ(P)- controlled inverters decrease LV-feeder voltages more than required to eliminate limit violations, resulting in excessive Q-exchanges between MV- and LV-grid, distribution transformer loadings and grid losses. The application of L(U)-control mitigates the social issues and improves the behaviour of LV-grids. Q-exchanges, DTR loadings and losses reach a remarkable minimum. Its combination with Q-Autarkic prosumers eliminates the load-related Q-flows completely. Reactive power flows through the LV-grid only if it is required for voltage control.

REFERENCES

[1] F. Katiraei and J. R. Aguero, "Solar PV Integration Challenges", *IEEE Power and Energy Magazine*, vol. 9, no. 3, 62-71.
[2] Technical Guideline – Guideline for generating plants' connection to and parallel operation with the medium-voltage network, 2008.
[3] "IEEE Draft Recommended Practice for Establishing Methods and Procedures that Provide Supplemental Support for Implementation Strategies for Expanded Use of IEEE Standard 1547", *IEEE P1547.8/D8*, 1-176.
[4] A. Ilo, "Effects of the Reactive Power Injection on the Grid—The Rise of the Volt/var Interaction Chain", *Smart Grid and Renewable Energy*, vol. 7, 217-232.
[5] A. Ilo, D.-L. Schultis and C. Schirmer, "A new Volt/var Control Strategy in Low Voltage Grids: Released Capacities by Q-Autarkic Prosumers", submitted to *Electric Power Systems Research-Journal-Elsevier*.
[6] A. Bokhari *et al*., "Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial, and Industrial Loads", *IEEE Transactions on Power Delivery*, vol. 29, no. 3, 1372-1381.
[7] E-Control, Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen, Version 2.3, 2016.
[8] O. Marggraf *et al*., "U-Control - Analysis of Distributed and Automated Voltage Control in current and future Distribution Grids," *International ETG Congress 2017*, Bonn, Germany, 2017, 1-6.
[9] Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on common rules for the internal market in electricity (recast), COM/2016/0864 final - 2016/0380 (COD).