TECHNO-ECONOMIC EVALUATION OF VOLTAGE DEPENDENT ACTIVE AND REACTIVE POWER CONTROL TO REDUCE VOLTAGE VIOLATIONS IN DISTRIBUTION GRIDS

Raphael Knecht*, Fabian Carigiet, Alain Schwab, Petr Korba, F. P. Baumgartner
[1]ZHAW, Zurich University of Applied Sciences, School of Engineering, IEFE
Technikumstr. 9, CH-8401 Winterthur, Switzerland, www.zhaw.ch/=kner
*phone: +41589344576; email: kner@zhaw.ch

ABSTRACT: High penetration of PV plants or numerous electric vehicle (EV) charging station stations connected to the low voltage distribution grids (LVDG) may cause a voltage rise or voltage decrease respectively. There are several measures of maintaining the voltage stability such as grid reinforcement, battery energy storage, line voltage regulator, etc., although they vary in effectiveness and economic viability. This paper focuses on using decentralised voltage-dependent active and reactive power (PQ(V)) control of PV inverters to stabilise the voltage in the grid. Using two grid models in Southern Germany and Switzerland the best PQ(V) control strategy is evaluated using load flow calculations. The weakest node in the first grid exhibits a maximum voltage of 1.072 pu on a sunny day. Due to the implementation of the PQ(V) control the maximum voltage is reduced to 1.024 pu at the same node. Costs considered for PQ(V) control are the PV yield loss and the additional reactive power compensation, which amount to roughly CHF 2'600.- per year. The future installation of EV charging stations may positively interact with PV feed-in. The voltage decrease can further be limited using PQ(V) control. Further grids and means for voltage stabilisation will be analysed in the future.
Keywords: Voltage Stabilisation, Grid Integration, Reactive Power

1 VOLTAGE VIOLATIONS IN LVDG

Voltage stability becomes an increasing concern for distribution system operators (DSO) due to increasing decentralised renewable energy generation and a large number of high power electric vehicle (EV) charging stations connected to the low voltage distribution grid (LVDG). Technical regulation in EN 50160 requires the voltage at a node in the LVDG to be within ±10% of the nominal voltage [1]. The D-A-CH-CZ-Regulations applied in Switzerland and Germany are more restrictively limiting the maximum voltage deviation to ±3% around the nominal voltage [2].

Measurements at a distribuation box in the LVDG of Dettighofen, Southern Germany (see Section 4.1) showed a voltage of over 110% of the nominal voltage for ten minutes on a sunny day in May 2014 [3].

The opposite voltage violation (below 90% of nominal voltage) is possible with an intermittent high power demand due to EV charging.

Distribution system operators need to find appropriate solutions to counteract these voltage violations when the PV penetration is high or a large amount of EV charging stations are going to be installed in their LVDG. Technical measures to improve voltage stability are:

- Grid Reinforcement
- On-load Tap Changer
- (Battery) Energy Storage
- Demand Side Management
- Line Voltage Regulator
- Active Power Curtailment
- Reactive Power Control

In order to provide results for a decision-making tool in the planning phase of a LVDG, ZHAW is evaluating and comparing both the technical as well as the economic feasibility of the above-mentioned measures for different grid classes. These grid classes were identified in collaboration with DSO and should contain the typical LVDGs in Switzerland:[4]

- Medium sized industry
- Small sized industry
- City border with shopping mall
- Urban neighbourhood with apartment buildings
- Urban neighbourhood with business
- Village centre
- Village periphery
- Hamlet

A combination of active and reactive power control using PV inverters is a promising cost-effective tool since no additional hardware costs arise. This method is presented in this work and its technical as well as economic viability is discussed.

2 REACTIVE POWER CONTROL WITH PV INVERTERS

PV inverters usually are programmed to feed-in only active power into the LVDG (cosφ = 1). The current induces a voltage drop across the line impedance ($|\underline{V}_{pv}| > |\underline{V}_{grid}|$) when active power is fed in. An additional reactive power injection will effectively reduce the voltage drop and thus reduce the voltage rise at the PV node (see [5]).

2.1 Different Control Strategies

There are several strategies for reactive power control using PV inverters like *fixed cosφ*, *cosφ(P)*, *cosφ(V)* and *Q(V)*. Their respective dis-/advantages are listed in Table I.

The voltage dependent reactive power control (*Q(V)*) is a decentralised approach since it only controls the reactive power according to the voltage at the location where the inverter is installed. Contrary to this, *fixed cosφ* and *cosφ(P)* both may cause excessive reactive power in the LVDG. *Q(V)* control also does not induce costs for real time control from a centralised location, apart from implementation costs.

Similarly to *Q(V)* the active power can be curtailed by the line voltage, henceforth denoted as P(V). The reduced active power feed-in also reduces the voltage at the PV node.

This decentralised method is implemented identically to the Q(V) control without any additional communication infrastructure.

Table I: Dis-/Advantages (-/+) of different methods for reactive power control using PV inverters.

Characteristic	**fixed cosφ**	**cosφ (P)**	**cosφ (V)**	**Q(V)**
Voltage Reduction	++	++	+	+
Voltage Rise	--	--	++	++
Reactive Power Input	--	-	+	+
Independent of Active Power	--	--	-	++
Effectivity for DSO	-	-	+	++
Effort of Implementation	++	+	-	-

2.2 Voltage Dependent Active and Reactive Power Control

A prospective control method is the combination of both *P(V)* and *Q(V)* control, denoted as *PQ(V)* control. The implementation is done by parametrisation of the PV inverters preferably at commissioning. There are already several inverters available on the market that provide this functionality [6].

The control ramps, as seen in Figure 2, define the relative active/reactive power feed-in as a function of the line voltage at the PV node. While an underexcited reactive power injection (from 0% at 1.01 pu to - 100% at 1.05 pu in example from Figure 2) leads to a reduction of the node voltage, the overexcited mode (from 0% at 0.99 pu to 100% at 0.95 pu in Figure 2) leads to a voltage rise.

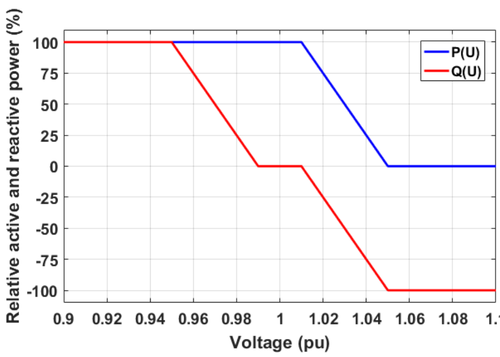

Figure 2: Example of control ramps for the reactive power feed in and active power curtailment as a function of line voltage in per unit (pu). The shown example is for a control strategy where 50% of the respective control bandwidth is reached at 1.03 pu.

3 COSTS OF PQ(V)

The implementation of PQ(V) control requires no communication infrastructure to a centralised station, instead costs for inverter oversizing, active power losses and additional reactive power compensation arise. These costs need to be included in the economic analysis for the comparison to the other methods presented in chapter 1.

3.1 Oversizing of inverter

When deploying 100% of the reactive power capability of the PV inverter (cosφ = 0.9), the rated apparent power output of the inverter has to be 1.11 times the active power output. Thus, the inverter has to be oversized accordingly:

$$S_{Inv} \geq \frac{1}{\cos(\varphi)} * P_n$$

The oversizing does not manifest a direct benefit for the PV plant operator and thus has to be reimbursed.

3.2 Losses

There are two types of active power losses which will arise with PQ(V) control. Active power curtailment will reduce obviously the effective yield of the PV plant. Furthermore, the reactive power feed-in will cause heat dissipation on the lines, resulting in active power losses in the LVDG. Both of these losses need to be included in cost calculations. They were quantified in Switzerland with roughly CHF 60.- per MWh.

3.3 Compensation of reactive power

There might be situations where the activated Q(V) control at multiple PV inverters will cause an imbalance of reactive power at the transformer to the next higher grid level. The compensation of reactive power is usually charged if the cosφ is lower than 0.92 at the transformer. If explicitly attributed to the Q(V) control this compensation needs to be included in the costs for PQ(V). The costs for reactive power were quantified with CHF 41.- per Mvarh.

4 LOAD FLOW CALCULATIONS

The voltage dependent active and reactive power control has been implemented to the load flow calculation software Matpower [5]. Using grid models provided by two DSOs, the two grid classes *village periphery* and *urban neighbourhood with apartment buildings* could be assigned. The technological analysis was performed over one year using the load flow calculation. Based on these results the costs could be identified.

4.1 Grid Class: Village Periphery

The western part of the LVDG in Dettighofen, Southern Germany (Village periphery) is connected to the medium voltage grid with a 400 kVA transformer (see Figure 3) and corresponds to the grid class *village periphery*. The installed PV capacity amounts to 535.5 kWp [3].

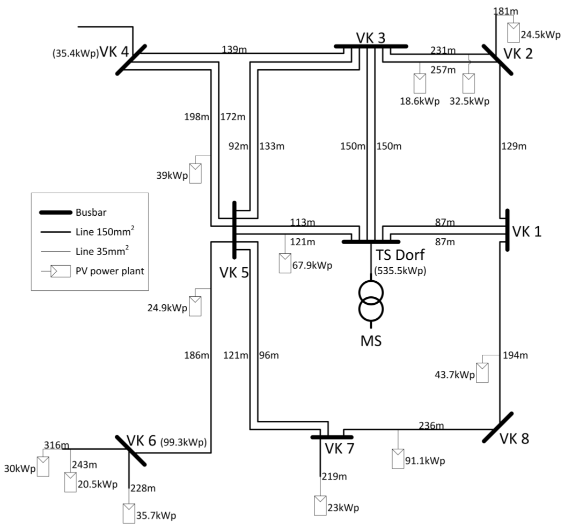

Figure 3: Single line diagram of the analysed grid part of Dettighofen. The transformer pictured in the center has an apparent power of 400 kVA. The grid features 33 PV plants with a total of 535.5 kWp nominal power.[5]

4.1.1 High PV Penetration

Additionally to measurements performed in 2014 [3], the load flow calculations without any control (status quo) identified a critical node at long stub connected to the distribution box *VK6* (see Figure 3). The voltage rise at the critical node reached a maximum of 7.23% above the nominal voltage. The distribution of the voltage in Figure 4 suggests that the load connected to this stub is relatively small compared to the installed PV nominal power. It can be seen that there are multiple instances of voltage violations beyond the 1.03 pu limit.

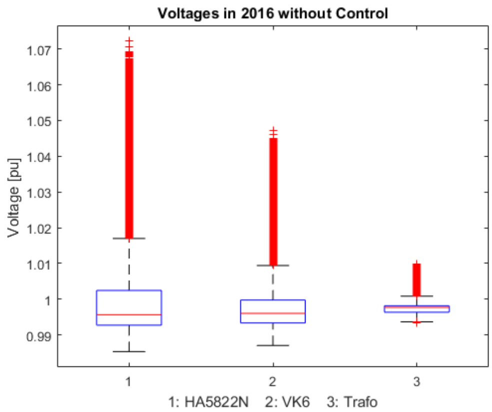

Figure 4: Voltage distribution (based on 10-minute mean values) at 1) the critical node, 2) the connection box of the critical node, 3) the transformer in Dettighofen followed from the load flow calculations without any control.

Several different control methods and ramps have been tested in the load flow calculation (see Table II).

The control strategy with the best performance regarding voltage rise limitation was PQ(V) with a mean of 1.02 pu (definition see Figure 2). With this inverter profile the voltage can be kept within the D-A-CH-CZ technical rules band at any time during the year (see Figure 5).

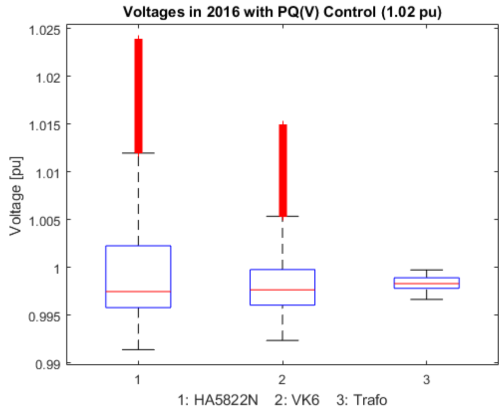

Figure 5: Voltage distribution (based on 10-minute mean values) at 1) the critical node, 2) the connection box of the critical node, 3) the transformer in Dettighofen followed from the load flow calculations with PQ(V) control with a mean at 1.02 pu.

Table II: Maximum Voltages over one year in Dettighofen, results from load flow calculations with different P/Q(V) control strategies.

Control Strategy	Maximum Voltage Critical Node	Maximum Voltage VK6	Maximum Voltage Transformator
Status quo	1.0723 pu	1.0471 pu	1.0098 pu
PQ(V) Mean 1.02 pu	1.0239 pu	1.0149 pu	0.9996 pu
P(V) Mean 1.02 pu	1.0282 pu	1.0203 pu	1.0049 pu
Q(V) Mean 1.01 pu	1.0466 pu	1.0243 pu	0.9962 pu
Q(V) Mean 1.00 pu	1.0430 pu	1.0206 pu	0.9993 pu

The yield losses, additional reactive power and the respective costs for the control strategies according to Table II have been computed (see Table III). The sole Q(V) control will reduce the voltage rise (although not below 1.03 pu), but the amount of additional reactive power in the LVDG is excessive, which is also reflected on the costs. The technically most promising solution (PQ(V), mean 1.02 pu) was also identified as the most cost-effective solution in this calculation.

Table III: Yield losses, additional reactive power and their respective costs over one year for the same control strategies as in Table II.

Control Strategy	Yield Loss	Additional Reactive Power	Cost per Year
PQ(V) Mean 1.02 pu	21.71 MWh	32.54 Mvarh	CHF 2’637.-
P(V) Mean 1.02 pu	46.68 MWh	--	CHF 2’801.-
Q(V) Mean 1.01 pu	--	417.36 Mvarh	CHF 17’112.-
Q(V) Mean 1.00 pu	--	745.75 Mvarh	CHF 30’575.-

4.1.2 EV Charging

Four hypothetical scenarios for EV charging in Dettighofen are assumed:

- No EV
- 1 EV at weakest node
- 50% of PV nodes with EV
- 100% of PV nodes with EV

The scenario 100% EV means that all nodes with a connected PV plant will also connect an EV charging station.

The charging is specified to happen during noon to investigate the interaction between EV charging and high PV feed-in. The charging profile is assumed the same for all EV, according to Figure 6.

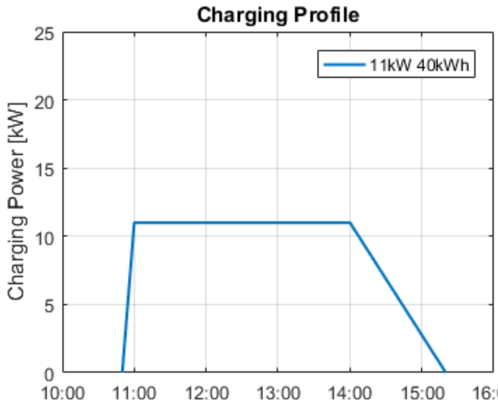

Figure 6: Charge profile used for the load flow calculations. The EVs (40 kWh) are charged during noon at a rate of 11 kW until they are 80% full. After that the charging rate is linearly decreased until SOC of 100% is reached.

Figure 7 shows the impact of EV charging on the voltage at the weakest node. While EV charging can limit the voltage rise due to PV power feed-in to some extent, it also will result in a voltage below 0.95 pu for the 100% EV scenario.

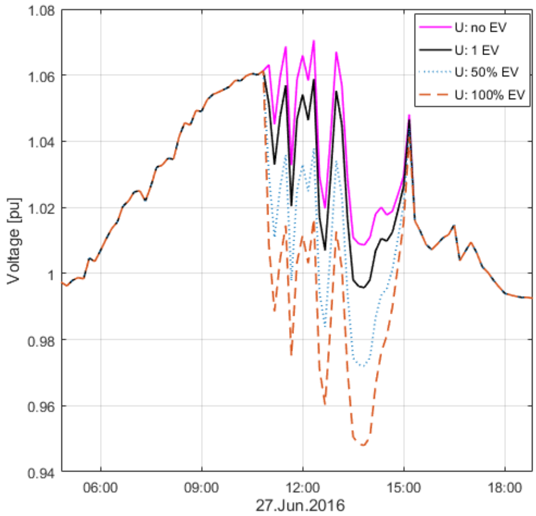

Figure 7: Voltage at the weakest node during a sunny day in June with the four EV scenario and without any control. The voltage decrease for 100% EV is visibly below the limit of 0.97 pu.

The voltage rise due to PV feed-in can be limited to 1.03 pu (see Figure 8) by implementing the PQ(V) control with a mean value of 1.03 pu (see Figure 2).

The voltage decrease due to EV charging is also limited within the limit of 0.97 pu by over-excited reactive power mode of the PV inverters, except for the 100% EV scenario.

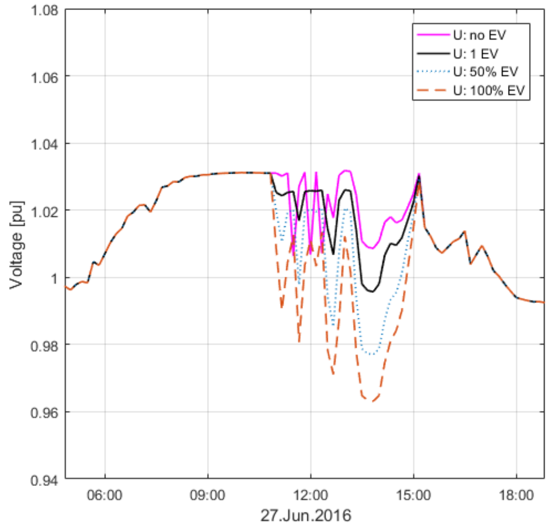

Figure 8: Voltage at the weakest node during a sunny day in June with the four EV scenario and with PQ(V) control with a mean value of 1.03 pu. The voltage decrease is limited compared to no control, although not quite within the limits for the 100% EV scenario.

4.2 Grid Class: Urban Neighbourhood with Apartment Buildings

The second analysed grid in Figure 9 is the current state of the small city of Ilanz, Canton of Grisons (Urban neighbourhood with apartment buildings), corresponding to the grid class *urban neighbourhood with apartment buildings*. The local DSO estimates a maximum of 41 PV power plants with a total nominal power of 788.5 kWp to be connected to their 630 kVA transformer in the future.

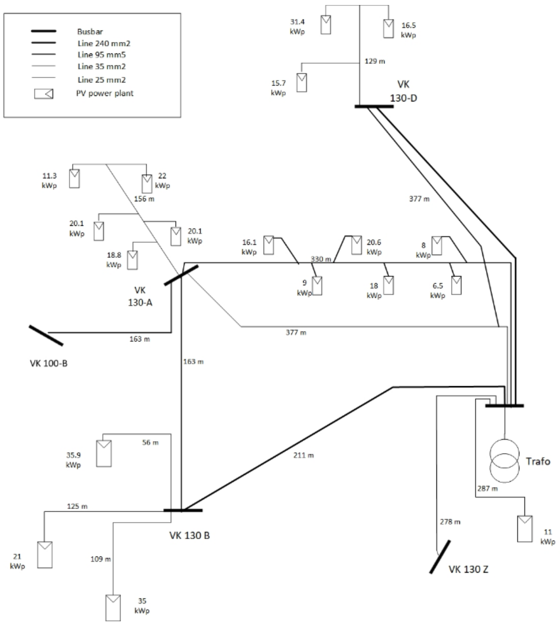

Figure 9: Single-line diagram of the grid in Ilanz, Grisons, Switzerland. The transformer has an apparent power of 630 kVA and the scenario estimates a total of 41 PV plants with a nominal power of 788.5 kWp to be installed in the future.

4.2.1 High PV Penetration

The load flow calculation without any control identified the critical node with a maximum voltage rise of 3.98% over the nominal voltage (see Figure 10).

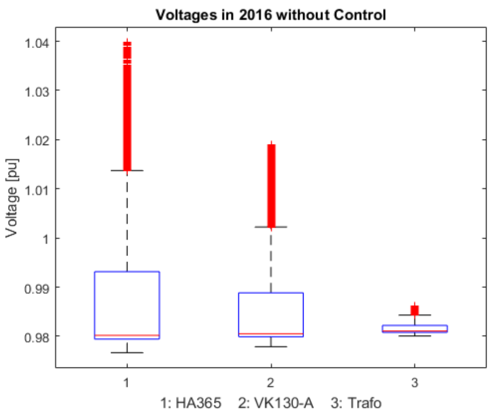

Figure 10: Voltage distribution (based on 10-minute mean values) at 1) the critical node, 2) the connection box of the critical node, 3) the transformer in Ilanz followed from the load flow calculations without any control.

Compared to Dettighofen the grid is more rigid since there are no long stubs with high PV penetration. This results in a lower maximum voltage rise at the weakest node (see Figure 10).

Different analyses with variation of the control methods show that the best performance could be reached with a PQ(V) control and a mean of 1.03 pu (see Table IV and Figure 11).

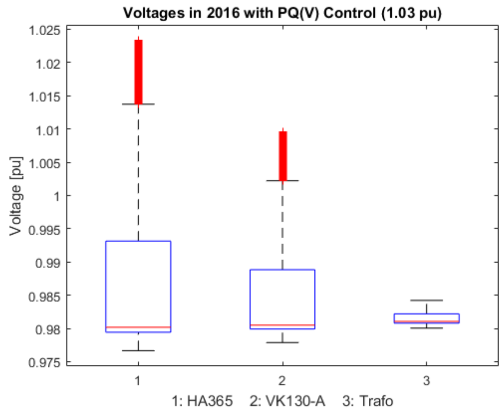

Figure 11: Voltage distribution (based on 10-minute mean values) at 1) the critical node, 2) the connection box of the critical node, 3) the transformer in Ilanz followed from the load flow calculations with PQ(V) control with a mean of 1.03 pu.

Table IV: Maximum voltages over one year in Ilanz, results from load flow calculations with different P/Q(V) control strategies.

Control Strategy	Maximum Voltage Critical Node	Maximum Voltage VK130-A	Maximum Voltage Transformator
Status quo	1.0392 pu	1.0185 pu	0.9861 pu
PQ(V) Mean 1.03 pu	1.0233 pu	1.0095 pu	0.9842 pu
P(V) Mean 1.03 pu	1.0249 pu	1.0116 pu	0.9850 pu
Q(V) Mean 1.02 pu	1.0295 pu	1.0094 pu	0.9832 pu

Table V: Yield losses, additional reactive power and their respective costs for the same control strategies as in Table IV.

Control Strategy	Yield Loss	Additional Reactive Power	Cost per Year
PQ(V) Mean 1.03 pu	4.16 MWh	--	CHF 250.-
P(V) Mean 1.03 pu	6.82 MWh	--	CHF 409.-
Q(V) Mean 1.02 pu	--	--	--

Again, the technically best control method causes the least costs regarding yield loss and additional reactive power compensation (see Table V). Although activated, the reactive power control does not cause the cosφ to go below 0.92, thus not inducing reactive power compensation.

4.2.2 EV Charging

The same scenarios as in Section 4.1.2 were assumed for the EV charging in Ilanz. It can be observed that there is a positive interaction between PV feed-in and EV charging, which complement each other to some extent in terms of voltage keeping (see Figure 12).

By applying the PQ(V) control with a mean of 1.03 pu the voltage deviation can be limited to ±3% of the nominal line voltage, although not for 100% EV (see Figure 13).

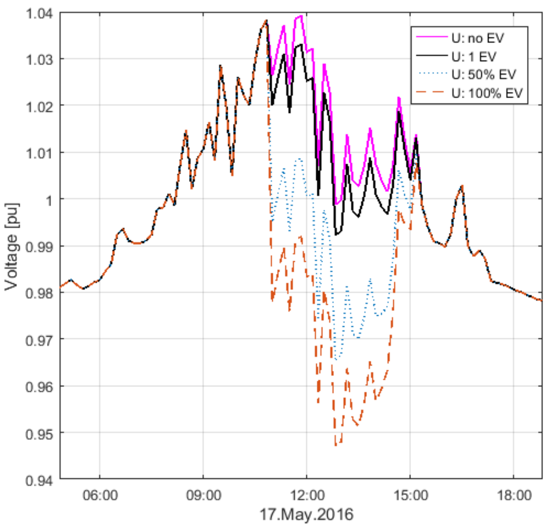

Figure 12: Voltage at the weakest node during a sunny day in May with the four EV scenario and without any control. The voltage decrease for 50% and 100% EV is visibly below the limit of 0.97 pu.

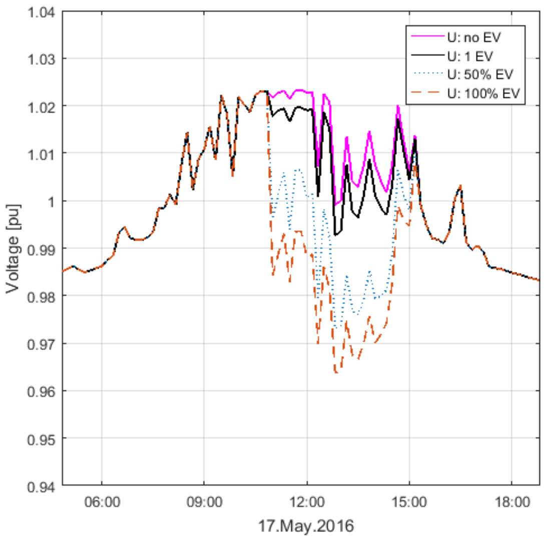

Figure 13: Voltage at the weakest node during a sunny day in May with the four EV scenario and with PQ(V) control with a mean value of 1.03 pu. The voltage deviation limits of ±3% can be met except for the 100% EV scenario.

5 CONCLUSION

The voltage dependent active and reactive power control was applied to two LVDG models using load flow calculation and a techno-economic analysis was carried out. It has been shown that PQ(V) control is a cost-effective and efficient approach to reduce voltage limit violations in LVDG with high PV penetration as well as in case of a large number of installed EV charging stations. The maximum voltage rise of 1.0723 pu could be reduced to 1.0239 pu using PQ(V) control in the case of the LVDG of Dettighofen. The yearly costs amount to CHF 2’637.- for this measure. The interaction between EV charging, PV and PQ(V) control has been proven positive under certain circumstances, reducing both the voltage rise due to PV feed-in as well as the voltage drop due to EV charging. Costs for different measures of voltage control, such as LVR, battery energy storage, etc., need to be acquired in order to compare the PQ(V) method. Furthermore, additional grid models need to be classified and analysed in the load flow calculation. The ultimate goal is to provide a decision-making tool for DSO to evaluate the most techno-economic measure for voltage stabilisation in their grid.

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