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Theme 2: Opportunities and Challenges with Operation using Flexibility

Modelling of low-voltage grids with high PV share and *Q*(*U*)-control

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Abstract: Climate challenges foster the integration of rooftop photovoltaic (PV) appliances. The associated inverters are often equipped with local *Q*(*U*) control to mitigate the voltage limit violations in low-voltage feeders. Their presence strongly modifies the behaviour of low-voltage grids. The common lumped model of the latter, which is used for load flow analysis in medium-voltage level, cannot describe their new behaviour. In this study, two lumped models of low-voltage grids are analysed and compared: the common or simplified one that does not consider the effect of the grid itself and the inverters' different working points in the *Q*(*U*) characteristic; and the exact one. Power flow simulations are performed in low- and medium-voltage test grids for maximal PV production. Results reveal high errors of the simplified lumped model that lead to incorrect power flow in medium-voltage grid.

1 Introduction

The behaviour of medium-voltage (MV) and low-voltage (LV) grids changes due to the large-scale integration of distributed energy resources. The active power injection of rooftop photovoltaic (PV) systems modifies the voltage profiles of the distribution feeders. To mitigate voltage limit violations, local $Q(U)$ control is often implemented in PV inverters connected in customer plant (CP) level [1]. In these conditions, the behaviour of the distribution grid should be carefully analysed to allow the highest possible PV share while ensuring the compliance with the operational limits. The power flow analysis requires the accurate modelling of the studied grid part and all connected elements [2]. Today, the proper lumped modelling of LV grids with $Q(U)$ controlled PV systems is a challenging task. In many cases, a simplified model based on the $Q(U)$ characteristic of the PV inverters is used. This study compares the simplified lumped LV model with the exact one. Their impact on the power flow calculations in MV grid is also analysed.

2 *LINK*-based power system modelling

The *LINK*-paradigm and the resulting *LINK*-based holistic architecture are used for power system modelling [3]. Therein, the entire power system is described using three main architecture components: Grid-Link, Producer-Link and Storage-Link; each one is composed of electrical appliances, the corresponding controlling schema, and the Link interface(s). The entirety of all electrical appliances included in a Grid-Link is denoted as 'Link-Grid'. To analyse the behaviour of a study Link-Grid, the study Link-Grid itself is modelled in detail. Meanwhile, lumped models are used for the connected elements. Fig. 1 shows an exemplary study Link-Grid with connected lumped models of neighbour Link-Grids, Producers and Storages. Each lumped model represents the $P(U)$ and $Q(U)$ behaviour seen from the corresponding boundary node of the study Link-Grid.

2.1 Link-Grid

The Link-Grid itself consists of lines, transformers and reactive power devices. It may apply to a CP, LV, MV or high-voltage (HV) grid. Producers, storages and neighbour Link-Grids are connected through its boundary producer, boundary storage and boundary link nodes (BLiN), respectively. Furthermore, consuming devices may be connected at boundary load nodes as long as they are not modelled as Link-Grids [4].

The lumped Link-Grid model represents the aggregate behaviour of the Link-Grid itself and all connected elements. It may inject or absorb active (P) and (Q) reactive power.

2.2 Producer and storage

The producer represents an electricity production facility that regulates its P- and Q-contribution locally. It may inject active power and inject or absorb reactive power. The storage represents a storage facility that regulates its P- and Q-contribution locally. It may inject or absorb active and reactive power.

3 Model description

Two distinct types of lumped LV_Link-Grid models are derived and analysed: simplified and exact. The same lumped model of CPs is used in both cases. Power flow simulations are performed in real LV grids. Furthermore, the impact of the lumped LV_Link-Grid models on the power flow analyses in MV level is investigated using two test feeders. Version 16.0 of PSS SINCAL is used for all simulations.

3.1 Lumped CP model

Three different categories of CPs are considered: residential, commercial and industrial. The used lumped CP model is shown in Fig. 2. It includes a consuming device model and a producer model; the impact of the CP_Link-Grid is not considered. The consuming device model relies on (1). Different *ZIP* coefficients are used for different CP categories [5]

$$\frac{P^{\mathrm{Dev}}}{P^{\mathrm{Dev}}_{\mathrm{nom}}} = C^Z_P \cdot \left(\frac{U}{U_{\mathrm{nom}}}\right)^2 + C^L_P \cdot \left(\frac{U}{U_{\mathrm{nom}}}\right) + C^P_P \tag{1a}$$

$$\frac{Q^{\mathrm{Dev}}}{Q^{\mathrm{Dev}}_{\mathrm{nom}}} = C^Z_Q \cdot \left(\frac{U}{U_{\mathrm{nom}}}\right)^2 + C^L_Q \cdot \left(\frac{U}{U_{\mathrm{nom}}}\right) + C^P_Q \tag{1b}$$

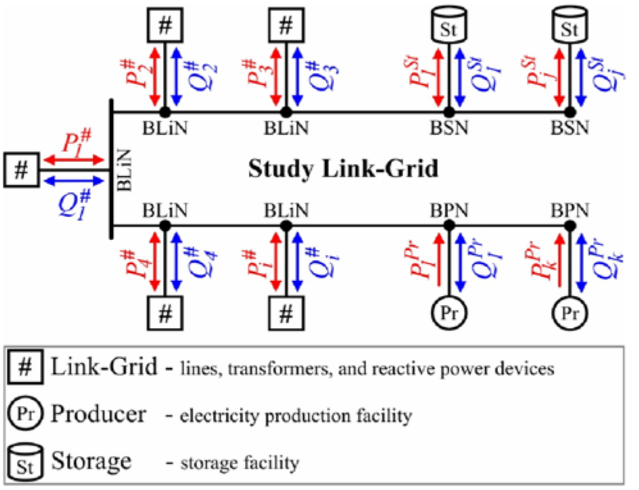

Fig. 1 *Study Link-Grid with connected lumped models of neighbour Link-Grids, producers and storages*

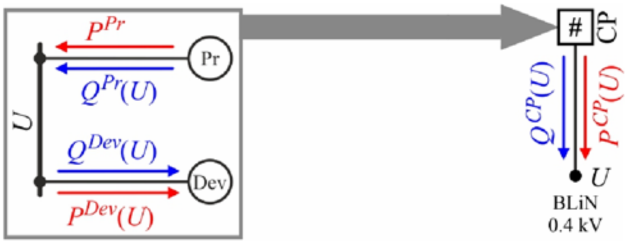

Fig. 2 *Lumped model of CPs*

$$C_P^Z + C_P^I + C_P^P = C_Q^Z + C_Q^I + C_Q^P = 1 \tag{1c}$$

$$Q_{\text{nom}}^{\text{Dev}} = P_{\text{nom}}^{\text{Dev}} \cdot \tan(\varphi_{\text{nom}}^{\text{Dev}}) \tag{1d}$$

where C_P^Z, C_P^I, C_P^P and C_Q^Z, C_Q^I, C_Q^P are the P- and Q-related *ZIP* coefficients; P^{Dev}, Q^{Dev} and $P_{\text{nom}}^{\text{Dev}}$, $Q_{\text{nom}}^{\text{Dev}}$ are the P- and Q-consumption of consuming devices for the actual and nominal voltage; U, U_{nom} are the actual and nominal voltages; and $\cos(\varphi_{\text{nom}}^{\text{Dev}})$ is the power factor of the consuming device model for nominal voltage. It is set to 0.95 inductive for residential CPs, and to 0.90 inductive for the commercial and industrial ones. The producer model implies a constant P-injection and a $Q(U)$ characteristic. It represents a PV system with an inverter, which is over-dimensioned according to (2a) to allow the power injection with $\cos\phi^{\text{Pr}} = 0.9$ also during peak PV-production periods. Their actual Q-contributions are determined by the $Q(U)$ characteristics shown in Fig. 3; depending on the type of superordinate LV_Link-Grid (rural, industrial, etc.), different characteristics are implemented in the PV inverters. In the simulated small urban and industrial LV_Link-Grid, voltage support is not needed. Consequently, $Q(U)$ control is not applied. Equation (2b) determines the maximal Q-contribution of the PV inverters.

$$S_r^{\text{Inv}} = P_r^{\text{Mod}}/0.9 \tag{2a}$$

$$Q_{\max}^{\text{Inv}} = S_r^{\text{Inv}} \cdot 0.4359 \tag{2b}$$

where S_r^{Inv} and P_r^{Mod} are the PV inverter and module rating; and $Q_{\max}^{\text{Inv}}$ is the inverter's maximal Q-contribution. A PV module rating of 5 kW is assumed for the residential CPs. The total behaviour of the lumped CP model is determined by

$$P^{\text{CP}}(U) = P^{\text{Pr}} - P^{\text{Dev}}(U) \tag{3a}$$

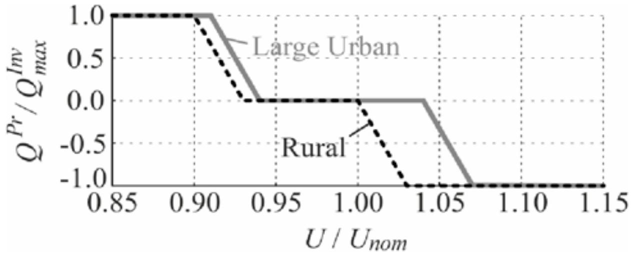

Fig. 3 *Q(U) characteristics of PV inverters within CPs connected to the Large Urban and Rural LV_Link-Grids*

$$Q^{\text{CP}}(U) = Q^{\text{Pr}}(U) - Q^{\text{Dev}}(U) \tag{3b}$$

One scenario with maximal PV production is analysed that represents the conditions prevalent at 12 p.m. on a sunny day. The corresponding values for the CPs connected to different LV_Link-Grids are shown in Table 1.

3.2 LV_Link-Grid models

The detailed LV_Link-Grid and lumped CP models are used to derive the simplified and exact lumped LV_Link-Grid models.

3.2.1 Detailed model of LV_Link-Grids: Four detailed models of real LV_Link-Grids with radial structure and a nominal voltage of 0.4 kV are considered: Large Urban (LU), Small Urban (SU), Rural (R) and Industrial (I) (Table 2). The tap changer of all distribution transformers (DTRs) is fixed in mid-position. The detailed data of the Large Urban and Rural LV_Link-Grids is given in [6]. Fig. 4*a* shows the generalised structure of LV_Link-Grids with the slack node located at the DTR's primary bus bar.

3.2.1 Simplified lumped model of LV_Link-Grids: This model is directly derived from the lumped CP model without considering the behaviour of the LV_Link-Grid. The simplified lumped LV_Link-Grid model consists of the equivalent consuming device and producer model (Fig. 4*b*). The behaviour of the

Table 1 *P*-consumption of the consuming devices for nominal voltage and *P*-injection of the producer within CPs connected to different LV_Link-Grid types

		Connecting LV_Link-Grid			
		LU	SU	R	I[b]
$P_{\text{nom}}^{\text{Dev}}$	kW	0.978	1.310	0.684	24.479
P^{Pr}[a]	kW	5.000	5.000	5.000	55.125

[a]Matches the installed PV module rating (max. PV production scenario).
[b]Average values for all connected CPs.

Table 2 Data of test LV_Link-Grids

LV_Link-Grid	Number of				DTR rating	Cable share
	F	CPs				
		Res.	Com.	Ind.	kVA	%
LU	9	175	0	0	630	96.14
SU	6	91	0	0	400	81.11
R	4	61	0	0	160	58.64
I	3	7	4	10	800	100.0

F: feeders; Res.: residential; Com.: commercial; Ind.: industrial.

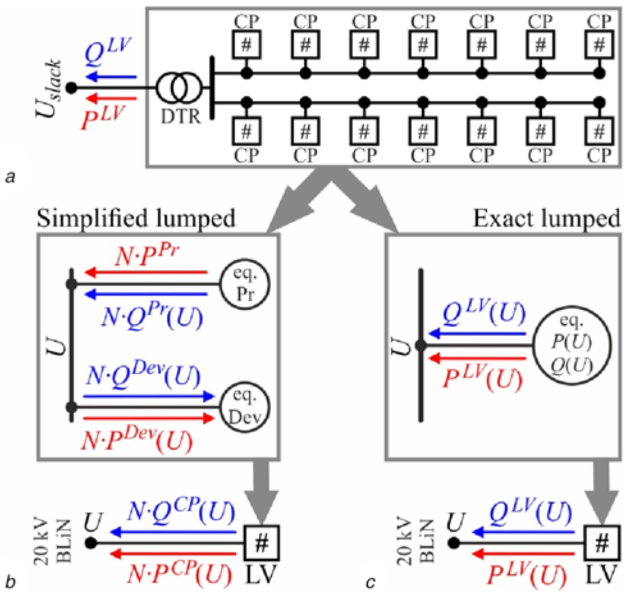

Fig. 4 *Modelling of LV_Link-Grids*

a Generalised structure
b Simplified lumped model
c Exact lumped model

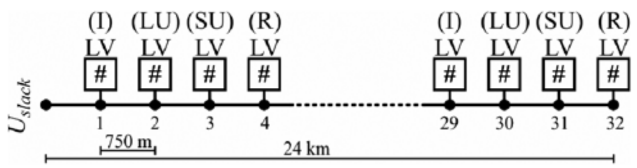

Fig. 5 *Structure of test MV feeders*

simplified lumped LV_Link-Grid model is determined by

$$P^{\mathrm{LV}}(U) = N \cdot P^{\mathrm{CP}}(U) \tag{4a}$$

$$Q^{\mathrm{LV}}(U) = N \cdot Q^{\mathrm{CP}}(U) \tag{4b}$$

where N is the number of connected CPs.

3.2.2 Exact lumped model of LV_Link-Grids: The exact lumped model represents the aggregate $P(U)$- and $Q(U)$-behaviour of the LV_Link-Grid itself and all connected CPs. This behaviour is calculated by repeating load flow simulations of the same scenario for gradually changing DTR primary voltages. The exact lumped LV_Link-Grid model represents the calculated equivalent $P(U)$ and $Q(U)$ characteristics (Fig. 4*c*).

3.3 Detailed model of MV feeders

Two theoretical MV feeders with a nominal voltage of 20 kV are considered: with cable or overhead line structure. In each of them are connected 32 LV_Link-Grids of different types, i.e. Industrial, Large Urban, Small Urban and Rural. Fig. 5 shows their structure. The slack node is located at the beginning of the feeder.

4 Behaviour of distribution grid

In the following are compared the simplified and exact lumped models of the different test LV_Link-Grids. Furthermore, the impact of these models on the resulting voltage profiles of both test MV feeders and on their $P(U)$ and $Q(U)$ behaviour at the boundary to the HV level is analysed.

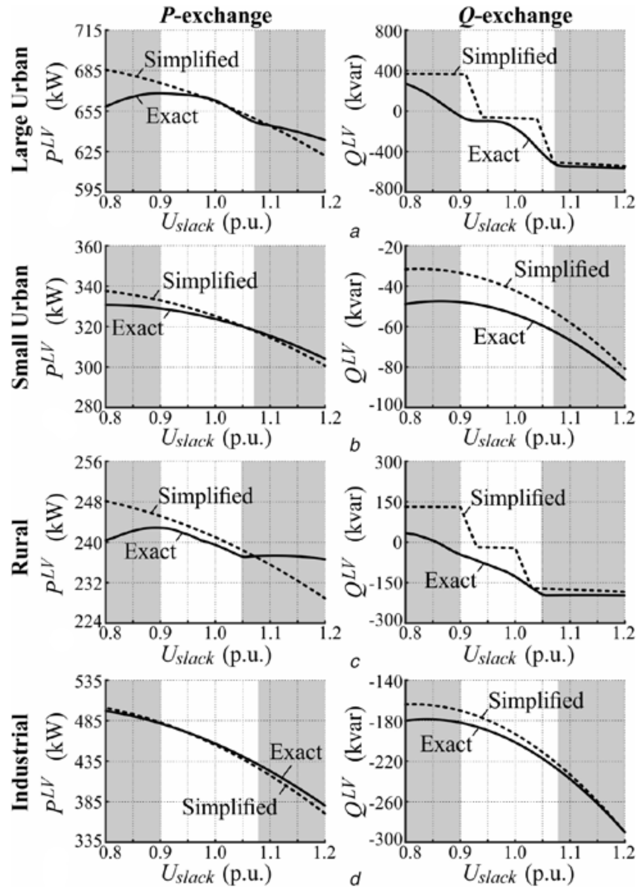

Fig. 6 *Behaviour of the simplified and exact lumped models of different test LV_Link-Grids*

a Large Urban
b Small Urban
c Rural
d Industrial

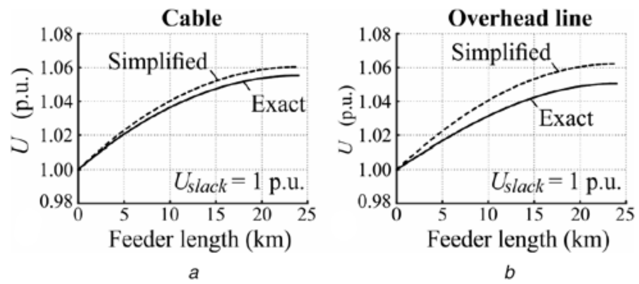

Fig. 7 *Impact of the simplified and exact lumped LV_Link-Grid models on the voltage profiles of two different MV feeders*

a Cable
b Overhead line

4.1 Behaviour of lumped LV_Link-Grid models

Fig. 6 shows the $P(U)$ and $Q(U)$ behaviour of the simplified and exact lumped model of different test LV_Link-Grids.

The DTR primary voltages that lead to limit (±10% of nominal voltage) violations within the detailed LV_Link-Grid models are shown with grey background, while the permissible ones have white background. The $P(U)$ and especially the $Q(U)$ behaviour of both lumped models differs considerably for all test grids. The simplified model behaves too capacitive. Maximum deviations of 441 and 176 kvar occur in the Large Urban and Rural LV_Link-Grid, respectively, within the permissible voltage range.

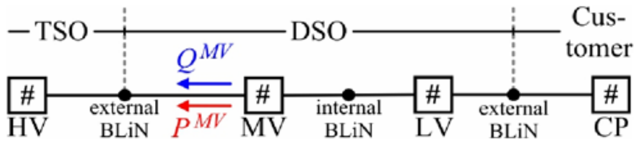

Fig. 8 *External and internal BLiN*

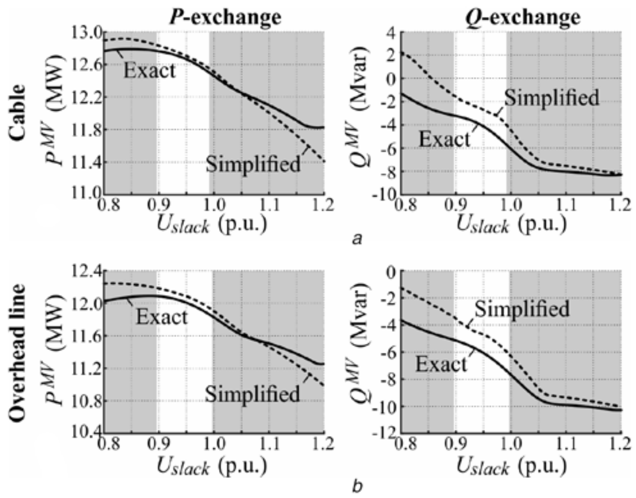

Fig. 9 *Impact of the simplified and exact lumped LV_Link-Grid models on the behaviour of two different MV feeders*

a Cable
b Overhead line

4.2 Voltages profiles of MV feeders

Fig. 7 shows the impact of the simplified and exact lumped LV_Link-Grid model on the voltage profiles of both test MV feeders for a slack voltage of 1.00 p.u. In both test feeders, especially in the overhead line one, the simplified lumped model provokes higher voltages than the exact lumped model.

4.3 Distribution system operator (DSO)–transmission system operator (TSO) interaction

Fig. 8 shows the external and internal BLiN between different power system levels. Different players are present: the TSO and DSO operate the HV, MV and LV_Link-Grids; while the customers own the CPs. In this section, the behaviour at the external BLiN between TSO and DSO seen from the HV_Grid-Link is analysed.

Fig. 9 shows the impact of the simplified and exact lumped LV_Link-Grid models on the $P(U)$ and $Q(U)$ behaviour of both test MV feeders. The aggregate behaviour of both MV feeders strongly depends on the used lumped LV_Link-Grid model. The use of the simplified one makes the P-exchange between TSO and DSO appear too high for low slack voltages, and too low for the high ones. Furthermore, it makes the distribution grid behaviour appear too less inductive.

5 Conclusion

Simulation results show that the simplified lumped model does not accurately represent the aggregate behaviour of LV grids with high PV share. Considerable deviations from the exact $P(U)$ and especially $Q(U)$ behaviour have been found in all investigated test grids. The simplified model behaves too capacitive. When $Q(U)$ control of PV inverters is active, the behaviour of LV grids strongly depends on the used lumped model: results for the simplified and exact model differ considerably. The same trend is observed in the case of MV calculations. The use of the simplified lumped model impairs the accuracy of load flow analysis significantly. It makes the MV feeder voltages appear too high and indicates a too capacitive behaviour of the MV feeders. Further analysis is needed for other load/production scenarios in CP level.

6 References

1 Ilo, A., Schultis, D.-L.: 'Low-voltage grid behaviour in the presence of concentrated var-sinks and var-compensated customers', *Electr. Power Syst. Res.*, 2019, **171**, pp. 54–65
2 Working Group C4.605: 'Modelling and aggregation of loads in flexible power systems' (CIGRE, 2014)
3 Ilo, A.: 'Link – the smart grid paradigm for a secure decentralised operation architecture', *Electr. Power Syst. Res.*, 2016, **131**, pp. 116–125
4 Ilo, A.: 'Design of the smart grid architecture according to fractal principles and the basics of corresponding market structure', *Energies*, 2019, **12**, p. 4153
5 Bokhari, A., Alkan, A., Dogan, R., *et al.*: 'Experimental determination of the ZIP coefficients for modern residential, commercial, and industrial loads', *IEEE Trans. Power Deliv.*, 2014, **29**, (3), pp. 1372–1381
6 Schultis, D.-L., Ilo, A.: 'TUWien_LV_TestGrids', Mendeley Data, 2018, v1