REACTIVE POWER PROVISION BY MEANS OF FLEXIBLE INDUSTRY CONSUMERS

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ABSTRACT

Due to the reduction of conventional electricity generation within the German grid new challenges arise. One of those challenges is how reactive power can be provided for the voltage regulation of the grid. A possible way to provide reactive power is the utilization of free converter capacities in the lower voltage levels. This paper focuses on the provision of reactive power by means of flexible industry consumers in the LV-network. The characteristics of an existing factory, which is intended for scientific research, at Technische Universität Darmstadt are used as an example of a flexible industry consumer. The reactive power provision capability for different levels of grid penetration with flexible factories is evaluated. In addition to the reactive power provision potential, the impact on the local distribution grid of the campus is analyzed.

INTRODUCTION

As a part of the German "Energiewende" the German government pursues a large increase of renewable energy sources (RES) share on the total net generation [1]. This increase of RES will be accompanied by a loss of conventional generation in form of coal and nuclear power plants [2]. In addition to the loss of electricity production, the reactive power provided by these conventional power plants will be lost. To ensure voltage stability of the grid it is necessary to find ways to provide reactive power [3].
Converters in general can be an easy source for the required reactive power. Already large numbers of converters are installed in modern grids and the numbers keep increasing [4]. The usage of solar inverters for the purpose of reactive power provision is already the subject of many studies which are very promising [5, 6]. These studies show that it is possible to provide a substantial amount of reactive power by utilizing the resources that are already connected to the grid. It has to be mentioned that this method usually increases losses within the grid.
Besides the solar inverters there is also a growing number of converters that are used within industrial applications. Most of these converters are used to power electrical motors that supply power to pumps, tooling equipment and other industrial appliances. Because these so called variable speed drives (VSDs) also offer a significant electricity saving potential their share in industrial applications is rising [7]. These converters can be used to provide reactive power for the grid. The fact that most of these converters are rated for the peak power demand of the connected motor leads to large converter ratings, which are only needed for a fraction of time. When the rated power of the converters is not required by the connected machine they can instead be used to provide reactive power.

PROJECT PHI-FACTORY AND GRID OF CAMPUS LICHTWIESE

Due to the mentioned energy saving potential of VSDs within the industrial manufacturing sector it is likely that their share will further increase in modern factories. The ETA-Fabrik showcases such a modern production facility. ETA-Fabrik (ETA-factory) is a federal funded research project and the name of a model factory that has been built on campus Lichtwiese of Technische Universität Darmstadt. It has been built to showcase how a factory could look like in the future. Within the factory a complete production process is recreated. The process is based on a real production process of the metal processing industry and includes typical steps such as tempering, milling and cleaning. All of those production steps are realized by equipment that is powered by converters.
Currently the ETA-Fabrik has a base load of approximately 25 kW and can reach a peak load of up to 65 kW during a production cycle. The factory hosts two CHPs with a combined rated electrical power of 15 kW and a combined rated thermal power of 35 kW.

PHI-Factory is the name of a follow-up project of the ETA-Fabrik project. The PHI-Factory project demonstrates ways to use communication networks within the factory and the production process to make the factory operation more flexible. This offers the possibility to participate in the energy markets by adapting the production depending on the energy prices [8]. Another possible use case is the provision of reactive power, which is subject of this paper.

The ETA-Fabrik is connected to the distribution grid of campus Lichtwiese, which is operated by Technische Universität Darmstadt. The grid structure of campus Lichtwiese is shown in figure 1. The grid has two medium voltage levels: 6 kV for the older buildings and the CHPs and 20 kV for the newer buildings. The 20-kV-level is connected to the public distribution grid. As it can be seen in the figure the grid uses an open ring structure. Both voltage levels are connected by two transformers with an apparent power of 3.15 MVA and an identical spare transformer. All three transformers are equipped with a tap changer. The

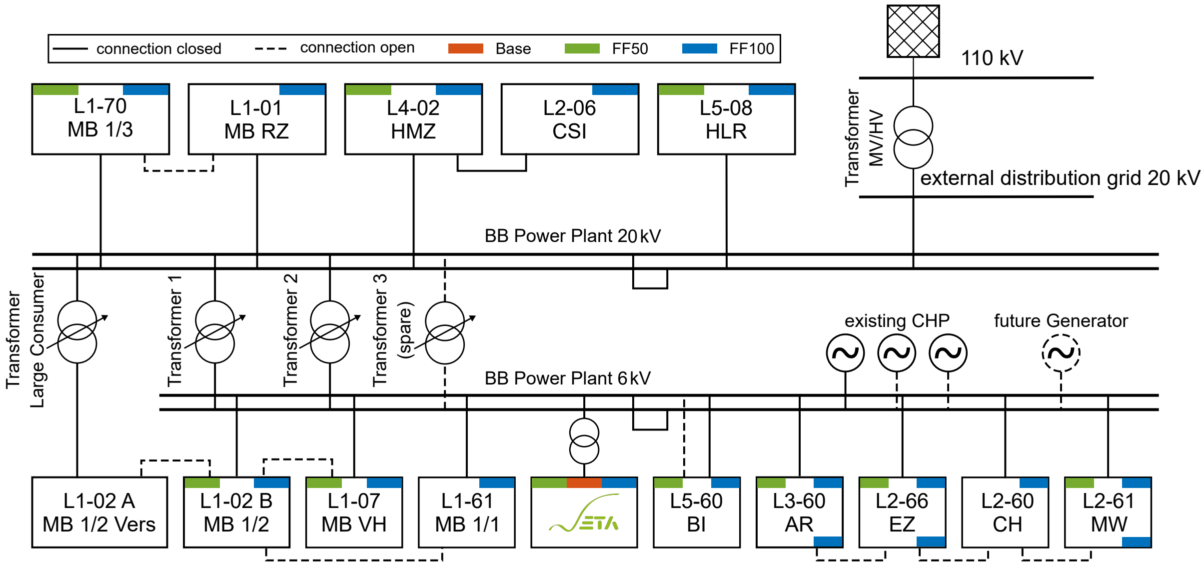

Fig. 1: Overview of the grid of campus Lichtwiese and the distribution of the FF-loads

power plant of campus Lichtwiese currently houses three CHPs with a rated electrical power of 2.4 MVA each. The load of the entire campus fluctuates between 2.5 MW and 5 MW. The reactive power consumption of the campus is inductive. The ETA-Fabrik is connected directly to the 0.4-kV-level of the power plant. In figure 1 every square represents a substation within the campus grid except for the ETA-Fabrik. Each substation consists of up to two MV-LV-transformers that connect the loads of the campus to the medium voltage level. The line length within the grid varies between 50 m and 840 m. The connection between the 110-kV-grid and the distribution grid consists of 3.5 km of cable and a transformer with a rated apparent power of 40 MVA.

MODELLING APPROACH

The results presented in this paper have been created with PowerFactory 2018 SP3. For the purpose of this paper a time frame of one week is analyzed. The time frame is based on a measurement that was conducted within the ETA-Fabrik and took place in June of 2017. Because the CHPs are heat lead, only one CHP is active during this time frame. The other loads within the grid are also modeled based on measurements conducted on the low voltage side of the MV-LV-transformers. A step size of 15 minutes is used for the simulations. For each time step one or multiple load flow calculations are conducted. The simulations are realized by a Python script that controls PowerFactory and manages the results for each time step. If a flexible factory (FF) load is added to a substation the active power consumption of the original load is reduced by the amount consumed by the FF load. The reactive power of the original load is scaled according to the change in the active power consumption. In the following subsection all relevant information about the distribution and behavior of the FF loads is presented.

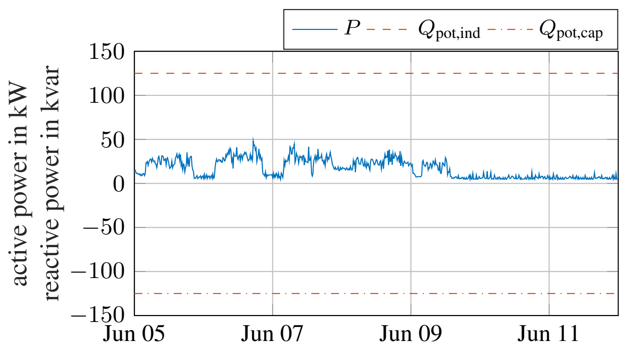

Fig. 2: Reactive power limits and measured active power consumption of ETA-Fabrik

Reactive power provision capability of ETA-Fabrik

The reactive power provision potential of each FF load is based on the characteristic of the ETA-Fabrik. The reactive power provision potential is shown in figure 2. As it can be seen the potential is 125 kvar for inductive power consumption and −125 kvar for capacitive power consumption. This potential is defined by the two large converters within the factory. The converter for the production machines has a rated apparent power of 150 kVA. According to the data sheet the reactive current can reach up to 50 % of the rated current of the converter. If the active power is higher than 75 kW the reactive power is reduced accordingly. As shown in the figure this is never the case for the given time frame. Therefore the converter can provide the full amount (75 kvar) for the whole duration of the simulation. The second converter is the converter of the hybrid energy storage system (HESS) that has a rated apparent power of 100 kVA. As there is no information about the loading strategy of the HESS available yet, it is assumed that the converter can also provide its full reactive power provision potential of 50 % (50 kvar).

Distribution of flexible factories

Different penetration levels of FF loads are evaluated. The distribution of the FF loads is indicated by the colored bars in the upper and lower region of the substations shown in figure 1. Each color represents a different scenario, which is explained in detail in the next subsection. If color bars are present in the top and bottom of a substation, this substation has two different transformers between medium low voltage level and a different FF load is connected to each of the transformers. The substation L1-02 A is used for large medium voltage consumers and is therefore neglected for the purpose of this paper.

Scenario definition

Four different scenarios are used. For each of these scenarios, inductive and capacitive reactive power consumption is evaluated. The results for each scenario are compared to a base scenario without any adaptation of the reactive power consumption. In the following sections a short description of each scenario is given as well as the reactive power provision potential (Q_{pot}).

The **Base** scenario consists of only the ETA-Fabrik as a FF load. There are three different variants of the Base scenario: the base scenario without any reactive power adaptation ($Q_{\text{pot,base,normal}} = 0\,\text{kvar}$), the inductive adaption of the reactive power consumption of the load ($Q_{\text{pot,base,ind}} = 125\,\text{kvar}$) and lastly the capacitive adaption of the reactive power consumption of the load ($Q_{\text{pot,base,cap}} = -125\,\text{kvar}$).

FF50 scenario shows the impact of an assumed penetration of 50 %. Therefore FF loads are connected to half of the substations (9 FF in total). The reactive power provision potential is $Q_{\text{pot,FF50,ind}} = 1125\,\text{kvar}$ and $Q_{\text{pot,FF50,cap}} = -1125\,\text{kvar}$.

FF100 assumes a penetration of 100 % (17 FF in total). The reactive power provision potential is $Q_{\text{pot,FF100,ind}} = 2125\,\text{kvar}$ and $Q_{\text{pot,FF100,cap}} = -2125\,\text{kvar}$.

FF100,max scenario is used to asses the maximum amount of reactive power that can be provided to the HV grid. In order to do so each FF load is scaled up by a factor of 5. To allow a higher degree of flexibility the tap changers of transformer 1 and 2, shown in figure 1, are used to adapt the voltage level of the 6-kV-grid. During the simulation the reactive power consumption is increased in small increments until either the loading limit or the voltage limit is violated. The limit for equipment loading is set to 80 % and the voltage for each busbar is allowed to reach values between 0.95 p.u. and 1.05 p.u. The theoretical reactive power provision potential is $Q_{\text{pot,FF100max,ind}} = 10\,625\,\text{kvar}$ and $Q_{\text{pot,FF100max,cap}} = -10\,625\,\text{kvar}$.

RESULTS

The main objective is to show the potential of FF to provide reactive power for the HV grid while showing the impact on the local grid to which the FFs are connected.

Figure 3 shows the reactive power exchange between the HV-grid and the MV-grid measured at the external grid. The base reactive power exchange of the campus grid is shown in black. The profiles for the Base with adapted reactive power provision, FF50 and FF100 scenarios have an offset compared to the base scenario. The offset correlates with reactive power provision potential of each scenario. The results for FF100,max is shown in purple. It can be seen that it is not possible to provide the whole reactive power potential while also remaining within all given grid operation limits. The results show that it is possible to consume more inductive reactive power than capacitive reactive power. The main reason for this is caused by the voltage limit, which will be discussed in detail later. The av-

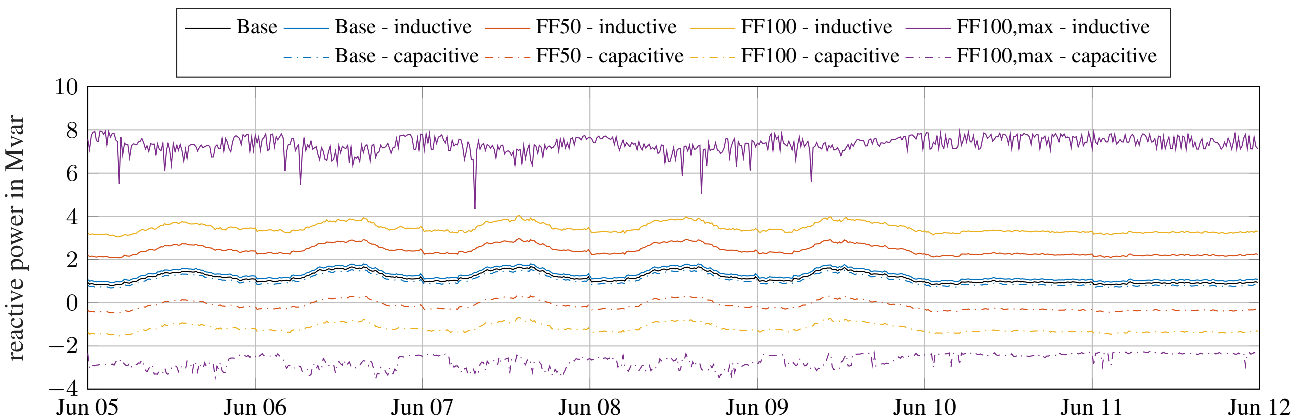

Fig. 3: Reactive power exchange with the external 110-kV-grid

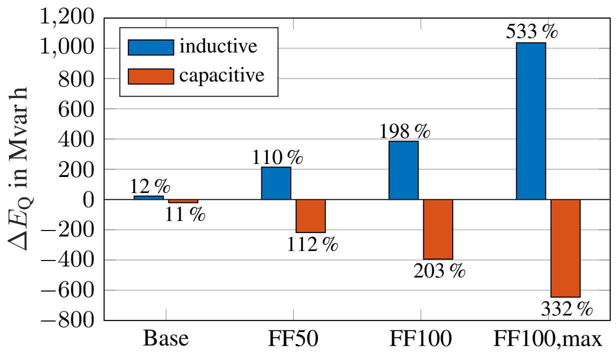

Fig. 4: Change in reactive energy exchange with the external grid compared to the base scenario

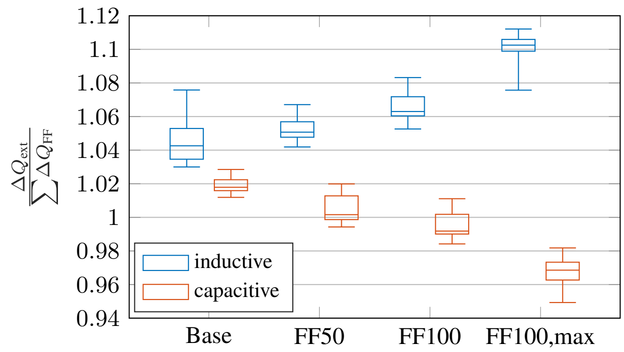

Fig. 6: Ratio of change of reactive power consumption of the FF-loads to the change of reactive power exchange with the external 110-kV-grid

erage amount of inductive reactive power that can be consumed by the campus grid is 7.33 Mvar while the average amount of capacitive reactive power that can be consumed is −2.69 Mvar.
The impact of the tap changers between the 20 kV and 6 kV level is pretty significant: Without the tap changers the average amount of reactive power that can be consumed is reduced to 2.92 Mvar and −1.52 Mvar respectively.

Figure 4 shows the change in exchanged reactive energy with the external grid. The result for FF100,max shows clearly that it is not possible to provide the whole amount of potential reactive energy. The amount of reactive energy that can be provided by the FF100,max scenario is in theory five times as high as in the FF100 scenario. For the inductive case the increase factor that can be realized is 2.69 and for the capacitive case it is 1.64.

Figure 5 shows the change in grid losses for the different scenarios. The losses for the Base scenario without any reactive power provision are 20.45 MW h. The increase of losses is significantly higher for the scenarios with inductive reactive power provision. This is due to the fact that the loads within the grid consume inductive reactive power. Therefore if the FF consume capacitive reactive power they will first compensate the local inductive reactive power demand and thus lead to a decrease in equipment loading that leads to a decrease in overall grid losses. This applies until the capacitive reactive power consumption of the FF loads exceeds the inductive reactive power consumption of the normal loads. This can be seen in the results for the FF100,max scenario. While the total amount of losses increases with each scenario the ratio of change of losses to change of reactive energy depends heavily on the scenario. The lowest ratio is 0.28 kW h/(Mvar h) for the scenario FF50 and capacitive reactive power consumption while the highest value is 26.49 kW h/(Mvar h) for the scenario FF100,max and inductive power consumption.

Figure 6 shows how much of the provided reactive power reaches the external grid. It is visible that the change of reactive power exchange at the external grid is larger than the change at each FF load for inductive power consumption. This is due to the fact that the increase of consumption at the FF loads leads to a higher current flow through the equipment such as transformers and lines that are inductive in nature and therefor increase the inductive reactive power consumption of the whole grid. Similar results occur for the capacitive scenarios: for low amounts of capacitive reactive power consumption of the FF loads the loading of the equipment is reduced and therefore the amount of in-

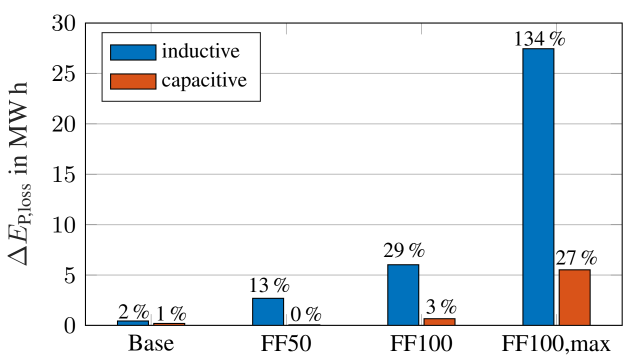

Fig. 5: Change in grid losses compared to base scenario

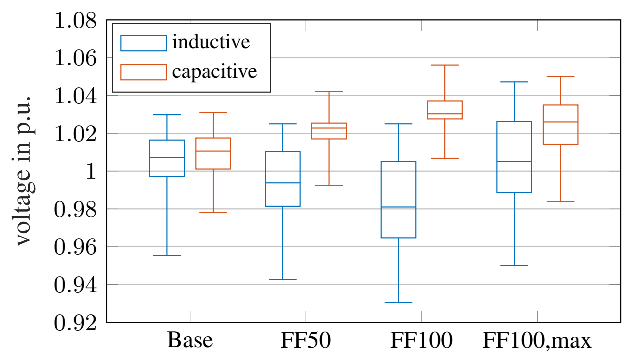

Fig. 7: Distribution of the voltage for all busbars within the grid

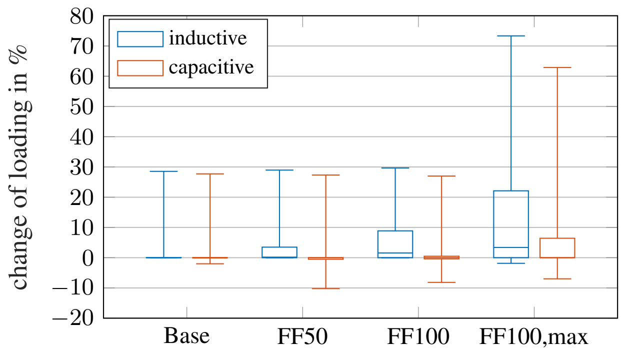

Fig. 8: change of equipment loading (lines and transformers) within the grid compared to base scenario

ductive power demand of the grid. When the amount of capacitive power consumption exceeds the inductive demand of the normal loads the loading of the equipment starts to increase again which reduces the change of reactive power exchange at the external grid.

Figure 7 shows the distribution of voltages for all busbars within the grid. As it is expected the overall voltage level decreases for the inductive scenarios and increases for the capacitive scenarios. Scenario FF50 and FF100 show that an uncontrolled adaption of the reactive power consumption can lead to voltage levels that are outside the limits. But as seen in the results for FF100,max this problem can be addressed with the tap changers of the transformers between the 20 kV and the 6 kV level while also increasing the amount of reactive energy that can be provided by the FF loads.

The change of equipment loading is shown in figure 8. The increase of loading for the majority of equipment is well below 10 %. The equipment that sees an increase in load is usually the equipment that is directly connected to the FF loads. For the cases Base and FF50 the cable between the ETA-Fabrik and the LV-MV-transformer is the only piece of equipment that sees a loading increase above 10 %. The majority of load increase for the FF100,max scenario is below 30 % with some exceptions with an increase of up to 73 %. The loading for all scenarios is always below 80 %.

CONCLUSION AND OUTLOOK

As seen in the results of this paper it is possible to provide reactive power to the high voltage grid by means of flexible industrial consumers. The reactive power provision is usually accompanied by an increase of grid losses, especially in case of the provision of inductive reactive power. The main limiting factor for reactive power provision in the grid of campus Lichtwiese is the voltage level at the busbars. The increase of equipment loading is generally rather low with a few exceptions. These exceptions can easily be fixed by simple equipment replacements. Besides the provision of reactive power to the external grid it is also possible to use the free converter capacities to reduce the overall grid losses of the campus grid by providing the necessary reactive power locally with flexible factories.

While this study shows the theoretical potential for reactive power provision on campus Lichtwiese a more practical question is how a specific amount of reactive power can be provided while also limiting the increase of grid losses.

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