THE INFLUENCE OF VOLTAGE-CONTROLLED TRANSFORMERS ON PV-PARK INVERTERS

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ABSTRACT

Technological innovations, economies of scale in manufacturing and innovations in financing have brought solar power generation within grid parity's reach in more and more markets.

However, one of the key challenges in project development remains to design a PV power plant that is optimally balanced in terms of cost and performance for a particular site. The performance of a PV power plant can be optimized through a combination of resources. In our case, an optimized combination of transformer with on-load tap-changer and central inverter is considered in the PV park: The permissible current carrying capacity of the selected semiconductor modules and the required AC input voltage range of the central inverter at a certain grid node set the limit for the transferable power of the inverter unit. We have investigated how the use of an inverter transformer with on-load tap-changer affects the transferable power of the inverter by providing a small optimised input voltage range to the AC side of the solar inverter.

This paper reports the results of a concept study, which shows that using a transformer with OLTC improves efficiency and increases the power of central inverters in PV parks.

INTRODUCTION

The focus of our considerations is on plants with outputs ranging from 10MW to several 100MW.

The fundamental components of a PV park.

In the following the components of a PV park (Fig. 2) are explained.

PV generator

The PV generator is the interconnection of a large number of PV modules connected serially and in parallel. An example is depicted in Figure 1.

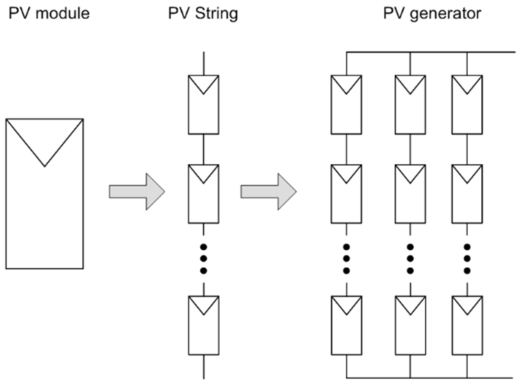

Fig. 1: Interconnection of PV modules to the PV generator

Central Inverter

These units convert the direct current supplied by the PV generator into alternating current and thus form the link between the PV generator and the load or the power grid. Inverters of this power class (>630 kVA) can be designed with an integrated transformer or without their own low-voltage transformer (transformer-less central inverter). In this case, an external medium-voltage transformer is needed to adapt the voltage.

Park transformer

Unregulated transformers are used to connect the transformer-less central inverters to the medium-voltage level. Depending on the system design, these transformers can be designed as two or three-winding transformers. The medium-voltage transformer transforms the low voltage supplied by the central inverter into a defined medium voltage.

PV park

In large PV parks, several central inverter units are directly connected to one or more medium-voltage transformers. Fig. 2 shows the system concept of a PV park, which is made up of the individual components described above. The transformers, which transform the output voltage of the inverters to medium voltage level, can be controlled with OLTC’s. This system concept forms the basis for our further investigations and simulations.

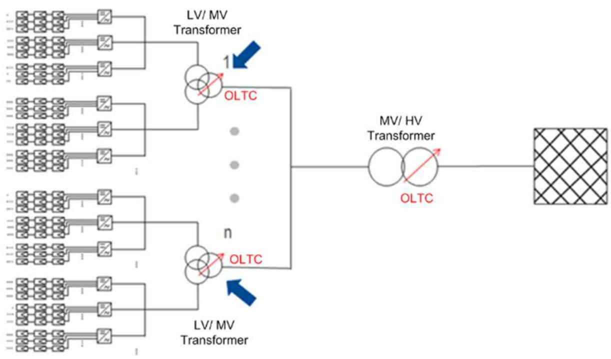

Fig. 2: PV park arrangement

Yield increasing manipulated variables

There are not many influencing factors available for optimizing the yield of the PV park. For this reason, the following section briefly outlines which parameters can be influenced and which cannot.

Non-adjustable parameters

The highest output power of a PV generator is achieved at the so-called Maximum Power Point (MPP). This current-voltage characteristic (Fig. 3) is mainly dependent on the cell temperature and solar radiation. As a consequence, differences in temperature and solar radiation on the PV module constantly change this characteristic. A so-called MPP tracker in the central inverter tries to dose the absorbed current in such a way that the MPP (the product of current and voltage) is reached, which enables the operation of the PV generator with optimum efficiency. This operation must always be guaranteed.

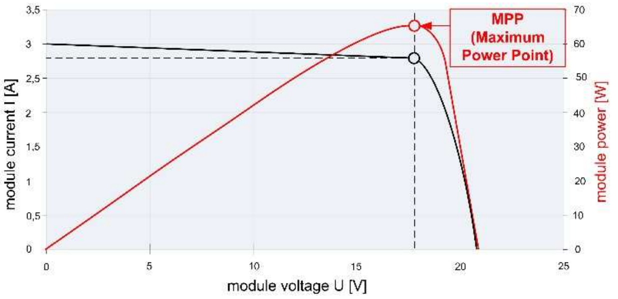

Fig. 3: Power diagram of a PV module [1]

The grid connection to the public transmission grid is standardized and fixed. As a result, it can be stated that the voltages within the park can be adjusted.

Manipulable parameters

The only sensibly manipulable variable within the park is the adaptation of the AC voltage directly to the central inverters. With a park transformer, whose transmission ratio can be changed during operation with an OLTC, it is possible to change the voltage within predetermined limits. This is interesting, because the cable losses increase squarely with the current. Thus, it should be attempted to operate the medium voltage level in the park constantly at the maximum allowed voltage.
An optimized operation of the inverters in terms of MPP, efficiency and transferable power is so enabled.

However, the available peak power of a PV generator must be fed into the public distribution grid via an inverter. This highlights that fact that the efficiency of the PV park also depends to a large extent on the design and operating parameters of the inverter, i.e., how the performance data of the PV generator and the inverter are matched to one another. A measure of this ratio is the "nominal power ratio”. This nominal power ratio (NPR) is used as a characteristic value. The NPR is the ratio of the DC power of the inverter (P_{DC}) and the PV generator power (P_{DCGen}) and is described by the following formula:

$$\mathrm{NPR} = \frac{PDC}{PDCGen} \qquad [1]$$

The “annual load duration curve” represents the cumulative energy yield of a PV park as a function of the operating time of the system (Fig. 4). This means that the PV park’s respective capacity is determined and applied depending on the number of hours in which this capacity arises. For example, the green graph shows that if the PV park is undersized compared to the inverter, any power peak can be processed by the inverters at any time, whereas if it is oversized (blue graph), the inverters are capped in about 2000 hours per year to protect them.
The following diagram shows how the different matching of inverter and PV generator affects the orderly annual duration line* of a PV- park.

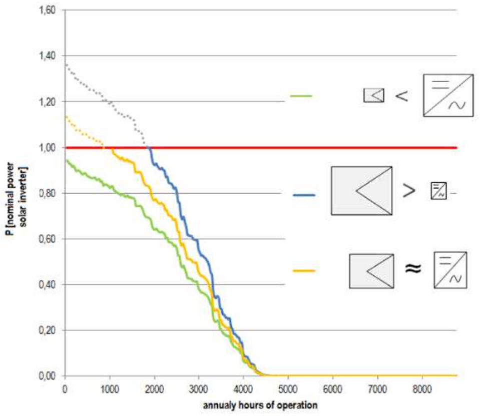

Fig. 4: Annually load duration curve of a PV park [3]

* The annual duration line represents the (cumulated and power-related ordered) energy yield of a PV- park as a function of the system running time.

Inverter sizing

Fundamental to our considerations is the case:

$$P_{DC} < P_{DC_{Gen}}$$

In countries such as Germany, the reason for undersizing the inverter is that the maximum power specified in the data sheet was determined under standard test conditions. In Germany, however, these only occur on a few days or hours. The system therefore works most of the time in partial load operation. Therefore, it makes sense to optimize the inverter for this partial load operation. But even in very radiation-intensive countries, where conditions are often even better than the STC (Standard Test Conditions), inverters are often undersized compared to the park. The reason for this is that a constant power output is desirable. The priority here is therefore a high number of full load hours, whereby the power peaks occurring for only a short time are sealed off in favour of this wish.

SIMULATION ENVIRONMENT

To investigate the influence of the OLTC on the central inverter and PV park yield, a central inverter model and a PV park model were developed. The inverter model is used to investigate the OLTC's effects on efficiency and power, while the park model is used to calculate the annual yield based on the results from the inverter model.

Simulation model inverter

In order to investigate the effects of the output voltage change on the inverter efficiency and output power, corresponding models must be developed. In most central inverters, the power electronic topology is the B6-bridge (Fig.5). The semiconductors (T1-T6) and the sine filter chokes (L1-L3) dominate the power loss in an inverter. The power loss of these components are strictly dependent on the temperature, voltage drop and the current to be conducted.

The Fraunhofer Institute for Energy Economics and Energy System Technology (IEE) carried out for us the investigations regarding the power electronics. [5]

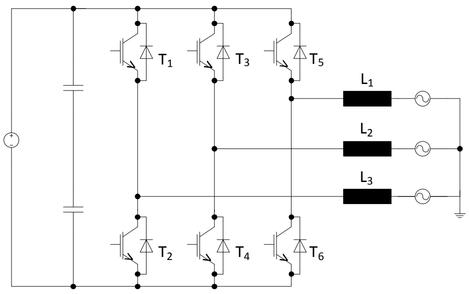

Fig. 5: Power electronic topology B6-bridge

For the power loss simulations PLECS® from Plexim was used. Infineon's state-of-the-art IGBT module FF100R12RT4 was chosen as reference power semiconductor module because it allows for simple measurements in the laboratory which function as a sufficient and representative basis for our simulations.

Simulation PV Park

In order to better illustrate the economic evaluation of these solution approaches, a complete PV park was modelled with realistic parameter settings. This PV park is designed for an output of 35 MW and consists of standard PV modules and inverters. All other necessary components such as cables and transformers are also standard components.

The simulation was carried out with the network calculation software PowerFactory® from DIgSILENT. In addition to the load flow calculation, the power losses of the individual components were also taken into account. 48 inverters with a P_{DC} = 713 kW are used, connected to 24 three-winding transformers which increase the voltage from low voltage (LV) to medium voltage (MV). Two PV generators were each connected to a three-winding transformer via a 315 V rail. These park transformers are equipped with an OLTC type ECOTAP VPD, which makes them adjustable.

Using the PV generator principle according to DIN EN 50530, the values for the active power of the generators were calculated over one year and fed into the simulation. The iron and copper losses of the transformers are calculated according to current regulations of the European Commission. [4]

SIMULATION RESULTS

Simulation boundary conditions and results for the central inverter

By means of simulation the following two scenarios were examined:

Efficiency improvement through variable output voltage at constant output power.

Increased power of the converter due to variable output voltage.

Succinctly, it can be stated that an increase of grid voltage with a voltage regulated transformer in the central inverter shows positive effects in terms of efficiency and power increase.

For testing the influence of an OLTC in terms of efficiency improvement of the inverter, the output power was kept constant and the simulation model was parametrized using the values listed in Table 1.

The results of the simulation show an increase in efficiency via increasing the AC grid voltage (Fig. 6). Furthermore, it can be seen that the efficiency increases in the direction of lower DC-Link voltage and rising grid voltage, where the increased grid voltage has the bigger impact.

Table 1: Boundary conditions for the efficiency improvement simulation

Parameter	**Value**
Output power	630 kVA
Power factor cos(φ)	1
Switching frequency	3 kHz
Input voltage / MPP-voltage	578 – 850 V
Output voltage / Grid voltage	284 – 364 $V_{LineLine}$ 164 – 210 $V_{LineNeutral}$ 181.8 $V_{LineNeutral}$ nominal
IGBT Module base plate temperature	100 °C

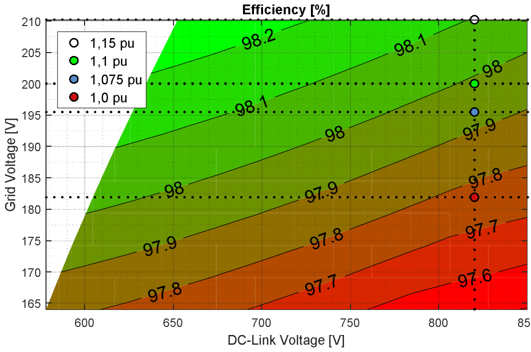

Fig. 6: Efficiency improvement through increased grid voltage at constant output power

Increased power of the converter due to variable output voltage:

For testing the influence of an OLTC in terms of increased power of the inverter, the output power was adjusted based on the semiconductor and choke power dissipation. Power loss was simulated for the operating point U_{DC} = 820 V and U_{AC} = 315 V_{LL} and set as the maximum value. If this power loss is exceeded for the semiconductors or the choke, an output power reduction takes place. If there are still reserves, the output power is increased. By limiting power loss, a thermal overload of the semiconductors or chokes is prevented. The maximum permissible values for the input and output currents were also kept within the permissible limits. The simulation model was parametrized using the values listed in Table 2.

Table 2: Boundary conditions for the increased power simulation

Parameter	**Value**
Output power	Variable
Power factor cos(φ)	1
Switching frequency	3 kHz
Input voltage / MPP-voltage	578 – 850 V
Output voltage / Grid voltage	284 – 364 $V_{LineLine}$ 164 – 210 $V_{LineNeutral}$ 181.8 $V_{LineNeutral}$ nominal
IGBT Module base plate temperature	100 °C

The results of the simulation show an increase in power by increasing the AC grid voltage (Fig. 7). For example, at the operating point of $U_{DC\text{-}Link}$ = 820 V, with an increase of the grid voltage by 15 %, the possible output power of the inverter can be increased by 15.2 %.

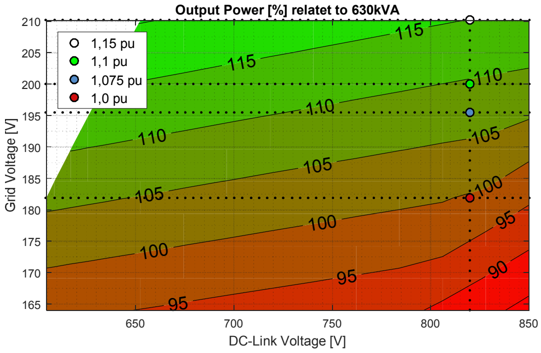

Fig.7: Power improvement through increased grid voltage

Table 3: Power transfer capability of the inverter at different AC voltage levels

Grid Voltage	Output power	Percentage
1 p.u.	630 kVA	100%
1,1 p.u.	690 kVA	109,5%
1,15 p.u.	723 kVA	115,2%

Simulation boundary conditions and results for PV park yield

The simulation is used to determine and compare how the energy yield of a PV park changes when regulated transformers are used instead of the unregulated park transformers.

The following situation was modeled for a simulated time series calculation:

The voltage at the inverter is kept at 1.075 to 1.1 p.u. by the OLTC control.

For this voltage range the linear interpolation of the values in table 3 leads to an increase of approx. 7% in the transmission capability of the converters.

With the time series of the solar radiation data of a typical park it was possible to achieve 4% more yield with the PV-park as shown in figure 8

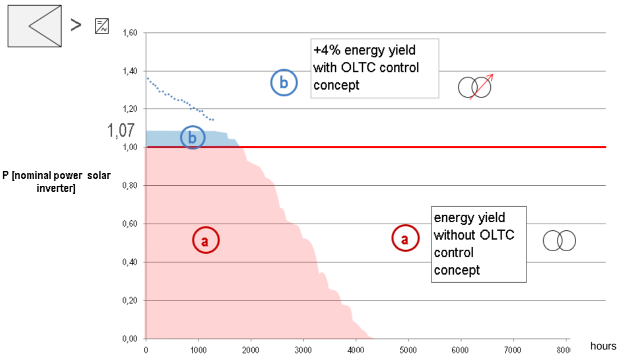

Fig. 8: Annual energy yield of a park marked in its load duration curve with and without OLTC control [2]

As feed-in volumes increase, so do losses in the PV park. Summarizing the simulation results for this PV park, it was found that an increase in inverter output over the entire year results in an increase in energy yield of 4%. Since it is known that the energy yield of a PV park additionally depends on solar radiation, our simulations support the hypothesis that supplying a PV park with OLTCs leads to a substantial higher energy yield in regions with higher solar radiation.

In the underlying control concept, automatic voltage regulation is only used in the park transformers. The control has been set so that the voltage value ranges between 1.07 p.u. and 1.1 p.u. The step voltage was defined to be 1.25 % of the nominal transformer voltage. The tap changer in the HV/ MV transformer [see Fig.2] has been set to a constant level 4. Because each individual transformer in the park is controllable, it is possible to regulate them individually according to the respective ambient conditions. In spite of requiring a more extensive control management, with this concept, the park is more fail-safe, as defects in the individual tap-changers do not affect the entire PV park
This simulation is merely an examination and evaluation of what is technically feasible.

CONCLUSIONS AND OUTLOOK

Unfortunately, our concept study has not yet been put into practice.
Nevertheless, the investigated interaction between transformers with an on-load tap changer and central inverters has shown that the adjustment of the alternating voltage has a positive influence on the efficiency and performance of the inverter. For example, the inverter can transmit up to 15.2 % more power at an alternating voltage of 1.15 p.u..
These results were used in a PV park time row calculation, which showed that increasing the inverter's transmission capacity of 7% leads to an additional energy yield of 4%.

Since both technical parameters (e.g. duration of sunshine, intensity of radiation) and economic parameters (e.g. feed-in tariff, investment costs, subsidies) determine the economic viability of a PV system, each PV park operator must, of course, assess the economic viability of our mode of operation individually on the basis of the specific economic framework conditions applicable to him.

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