CONTROL ALGORITHMS FOR PHOTOVOLTAIC INVERTERS WITH BATTERY-STORAGE FOR INCREASED SELF CONSUMPTION

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ABSTRACT

The aim of this paper is the development and analysis of control algorithms for internal energy management systems in interactive grid solar inverters with a battery storage system. Therefore, such a system consisting of multiple power electronic devices and a lead acid battery is described. Three different energy management algorithms are developed and simulated with different load and production data to gain results which allow to compare the features of the control algorithms. One of the main results are achievable self-consumption-rates which play an enormous role in the cost-effective operation of private photovoltaic (PV) power systems. The simulations were carried out in MathWorks MATLAB for a time span of one year in one-second resolution. This allows a detailed analysis of the different algorithms. Special attention is paid on the time resolution of the power measurements where a significant dependency on the achievable self-consumption-rate has been found.

Keywords: photovoltaics, battery storage, energy management, self-consumption

1. INTRODUCTION

At the moment PV-systems are divided into two groups. On the one hand there are island systems for powering remote users which have no or a very poor connection to a distribution grid. The second type of PV power plants are grid connected systems which faced an enormous increase in the last years. About 175 MWp of grid connected PV systems have been installed in Austria in 2012 which is nearly the double amount of the installed capacity in 2011 (Biermayr et al., 2013). The main part of this capacity is connected to the low voltage transmission grid where in times with high insolation a power flow in reverse direction (from the low to the medium voltage grid) can take place. As a consequence the voltage can reach incorrect levels.

Additionally, due to the decreased prices for photovoltaic (PV) systems subsidies mainly in Germany and Austria are cut strictly. Especially for private users it gets attractive to use as much solar energy as possible themselves. Beside the adaption of the time behaviour of the electricity use it is also possible to store the PV-energy for the use at times with higher electricity demand in the household. Therefore inverter systems with battery back up came on the market especially for grid connected usage.

This allows the costumer to store excess energy and increase the self-consumption-rate and it supports the grid by the reduction of the maximum feeding power if appropriate control algorithms are used.

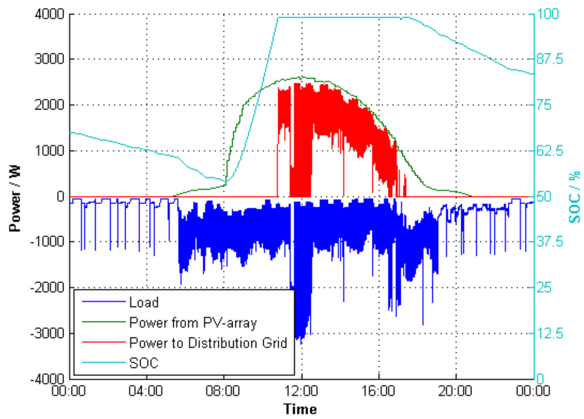

Figure 1: Power flow on a cloudless day.

In figure 1 power curves of an exemplary cloudless day are shown. On the second Y-axis the state of charge (SOC) of an integrated battery is assigned. The figure shows that the storage is not fully discharged from the day before and the maximum state of charge is reached around 11 o'clock a.m.. Afterwards the power on the connection to the transmission grid is equal to the power production of the PV-system minus the load.

2. SYSTEM DESIGN

In this work a photovoltaic inverter is used that combines the features of island- and grid connected converters. As shown in figure 2 a battery, in our case due to economic reasons a lead acid battery with 48 V system voltage is connected via a DC/DC converter to the intermediate direct current link. This circuit is fed by a DC/DC converter acting as a maximum power point tracker and connected to the household grid via an inverter which can be uni- or bidirectional. The latter enables the charging of the battery from the grid which is necessary to prevent the storage from deep-discharge or opens the possibility to grid-dependent load leveling as it is described later.

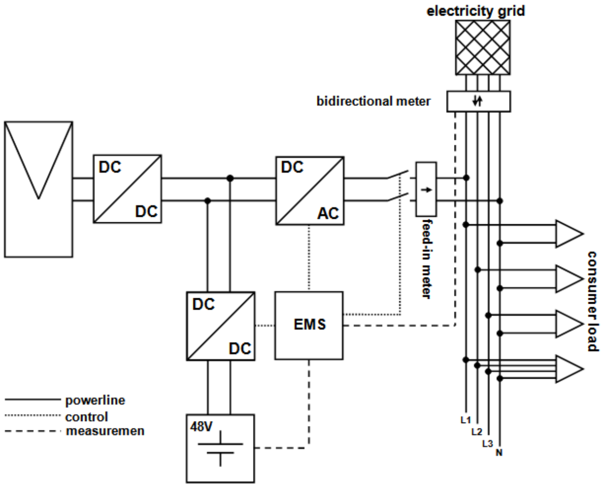

Figure 2: Design of discussed inverter system.

In this work DC-coupling of the storage is used. Alternatively AC-coupling is also possible with the advantages of flexibility in dimensioning the single devices. On the other hand an additional power-conversion step is necessary which increases the system losses. Grater detail is presented in Rechberger (2012).

2.1. Control

During operation of such systems a number of measured values have to be evaluated and the particular control algorithm has to be executed. Therefore a control system is necessary which is illustrated as ‘Energy Management System (EMS)’ in Figure 2. This central system is responsible for the correct and efficient operation of the inverter. Due to the small storage capacity of the intermediate circuit the control has to be very precise.

Ding et al. (2010) presented an alternative control scheme where the voltage value of the intermediate circuit acts as the only control variable. Every power conversion part of the system has its own control algorithm focusing on the voltage. The storage DC/DC converter acts as a superior system keeping the intermediate voltage constant. This is realized by withdrawing energy from the circuit if the value is to high and using energy of the battery to increase the voltage if it is too low.

2.2. Emergency Function

Such hybrid inverter systems can also be used as a kind of emergency system. In general inverters of grid connected PV power plants have to be switched off in case of grid failure. This means that if a grid outtake happens, a PV system is not allowed to feed in the grid because of security reasons. Because normal grid connected inverters are not able to work as an island inverter, the operator cannot use the PV system to power his loads.

If a hybrid inverter with energy storage functionality is used and the legal requirements like a self-acting disconnection point are fulfilled an island system can be built up. An important point herby is the capacity of the storage which limits the time of self supply. It could be an option to reserve a part of the capacity of the battery in order to support critical loads during grid outtakes. However, it must be kept in mind that this part of storage capacity cannot be used in self-consumption mode.

3. CONTROL ALGORITHMS

In this paper three different energy management strategies are developed. In the following section the control algorithms are described and evaluated for simulation. Further information can be found in Rechberger (2012).

3.1. Own Consumption Strategy

The goal of this scenario is the increase of the own consumption rate which shows the difference between produced energy and energy fed to the grid at the rate of the converted PV energy.

According to Castillo-Cagigal et al. (2011) this results in balancing the power flows in the system. The battery is charged if the photovoltaic power increases the load power as long as it is not fully charged. If the storage system is not able to accept further energy this excess energy is fed into the grid. On the other side the battery is used to power the load up to the maximum power of the inverter/battery system when the load increases the PV power as it is for example during the night or at cloudy days.

In addition to the state of charge (SOC) of the storage system the exact measurements of the power flows are necessary. The determination of the SOC depends mainly on the type of battery used in the system. While modern lithium based batteries usually require a battery-management-system which measures the charge level internally, separate systems for lead acid batteries are needed. The calculation of the SOC is mostly carried out by balancing the energy charged and discharged by the battery or measuring the voltage and calculating the current capacity by the use of characteristic curves. In order to measure the power flow current transformers or energy meters with appropriate output signals can be used.

To increase the expected lifetime of the battery different optimization strategies are integrated. These contain the limiting of the operating SOC range with frequent equalisation charges. Additionally a hysteresis around the full and empty state of charge was implemented to prevent the storage from numerous micro-cycles.

The battery model itself was based on a simple energy-balance model without chemical background.

Because of the constant use of the battery as an active storage system self-discharge was neglected.

3.2. Variable Tariffs Scenario

Electricity system operators in Austria (Traxler 2011) try to appeal the shifting of electricity consumption of the customers by the use of time variable tariffs as a method to delay expensive investments in system improvement.

The use of a storage system could therefore be a solution for the customer not to shift his consumption actively but via the battery. If the progress of electricity tariffs is known in advance the battery could be charged during cheap times directly from the grid while being discharged in expensive times trying to reduce the electricity demand from the grid to a minimum. Weather forecast could be an additional advantage in this process and will be a part of future works.

3.2.1. Development

A dynamic simulation was used to determine the optimal functionality of this strategy. Through artificial load and production curves the simulation chose the way to reach the lowest costs after one day of operation. After a number of runs over different days the optimal sequences were applied to the final variable tariffs scenario.

For one example day the initial and final state of charge was defined. To reduce the requirements of the calculation fixed SOCs were established in between at a time resolution of one minute. Between the single steps the energy required or provided by the battery was transferred by a cost function into absolute energy costs. The simulation resulted in a enormous number of possible ways to reach the goal of a fixed SOC. Different, artificial load and production curves as well as tariff-scenarios were used in multiple simulations. Finally the overall cheapest ways for each scenario were visualised and manually analysed.

It has been found out, that the optimal ways follow the supposed actions, which are:

- In case of a constant electricity tariff the most cost effective model is the own consumption strategy.
- If the feed-in tariff exceeds the consumption tariff including the battery storage costs the alternating charge and discharge respectively the buying and selling of energy is recommended.
- If the tariff increases the battery should be charged to be able to power the consumer loads. Due to the fact that no external weather forecasts were used in this work, the energy production of the previous day is used to predict the optimal state of charge before high energy prices and as well to reduce the amount of bought energy.
- Potential equalising charges should be arranged in low-priced or sunny stages.

Summing up this strategy, the battery is mainly used for load levelling in the household with an advantage of a photovoltaic system.

3.3. Optimised Battery Usage

As already mentioned in reference to the own consumption strategy, the battery lifetime has an enormous impact to the overall costs of such hybrid systems. Therefore an additional strategy was simulated with special adjustments to increase battery lifetime.

For example the depth of discharge (DOD) was reduced to a minimum in dependence of the time of year to minimise states with a low state of charge during times with reduced irradiance like winter. Additionally, the maximum charge current was developed as a function of the SOC which means that charge power is reduced at high and low SOCs to prevent the battery from overheating. To further reduce the number of micro cycles the working state of the battery is changed in intervals of only 30 minutes. Therefore the mean load and production power of the last interval is essential for further operation.

4. SIMULATION

The different energy management algorithms were converted in MathWorks MATLAB scripts which were used to simulate one year of operation. Different load, production and tariff curves were used. To represent a realistic operation measured data of a real PV-system and of multiple households were utilised.

4.1. PV-Data

The data of the PV system was recorded in 2010 in Upper Austria with a sample rate of 300 s. The system is orientated to south-east with an inclination of 25 °. The original power of 4 kWp has been scaled to two datasets with a capacity rating of 3 and 5 kWp respectively.

4.2. Load-Data

The big advantage of this work is, that realistic and high resolution consumer load curves are used. This data originates from the "ADRES-CONCEPT" project, where a dataset for electricity measurements in Austrian households was generated. The measurements were carried out for two weeks of one year (Adres 2011).

To use the data in this work three household-datasets were taken and extrapolated to one year of data. Thus, different household profiles could be represented:

- A double-person household with an annual electricity demand of around 3 MWh.
- A four-person household with an annual electricity demand of around 4.6 MWh.
- A six-person household with an annual electricity demand of around 6.6 MWh.

4.3. Additional boundary conditions

A lead acid battery with a nominal voltage of 48 V and a capacity of around 10 kWh was used as storage unit. Due to the fact that this work brings the topic of energy management into focus the battery has been realised in the simulation as a black box model with charging efficiencies taken from Sauer, Leuthold, Magnor and Lunz, 2011.

For cost calculation an energy price of 0.2 € per kWh for buying and 0.08 € per kWh for feeding energy into the grid were used. In case of time dependant tariffs a price of 0.3 € per kWh was used from 6 a.m. till 6 p.m., while 0.1 € per kWh was used in the remaining time.

As already mentioned the time resolution of self-consumption and variable-tariffs scenario lie in the order of one second, while the battery optimisation algorithm was simulated in intervals of 30 minutes.

5. RESULTS AND DISCUSSION

In the following section the main results of the simulations are presented.

Figure 3 shows achieved self consumption rates of six different options combining the two PV and three consumer load curves. It can be seen that the self consumption increases around 30.3 % if the own consumption strategy is used. The highest rate is achieved if a small PV-system is combined with a high load. The optimised battery usage algorithm performs relatively poor in contrast to the other energy managements. This is a result of the multiple restrictions taken in order to expand battery lifetime.

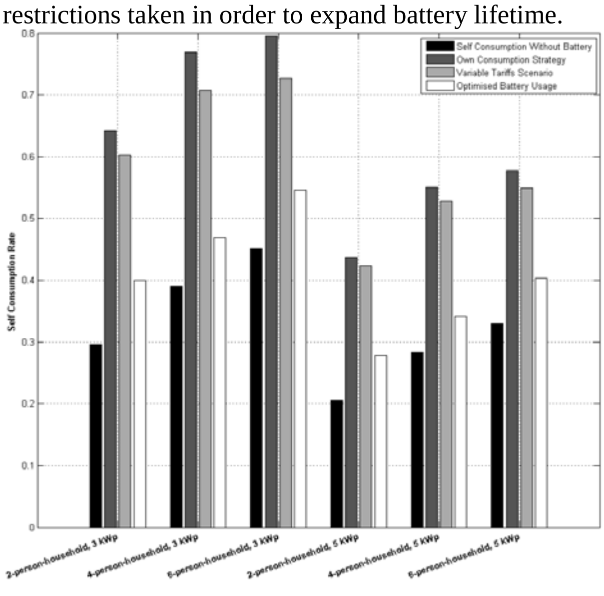

Figure 3: Self Consumption Rates of Different Energy Management Strategies.

In figure 4 the energy throughputs of the battery with different energy management strategies are shown. As expected the battery optimised strategy reduces the throughput significantly. In comparison to the variable tariffs scenario a bisection is nearly possible. Nevertheless the own consumption strategy shows the highest increase in self consumption rate in combination with a medium energy throughput. This means that it is the most effective strategy referring to the energy throughput. It reaches an annual throughput between 1150 and 1350 kWh which is around a hundred times the capacity of the battery which can be seen as 100 full cycles. Taking the lifetime of a standard lead acid battery into account, vague lifetime predictions could be made. But to do so, further battery- and model-specific factors have to be taken into account.

Table 1 shows a financial view of the problem. The energy costs of one year of operation were calculated and compared to the cost which occur for the households if no PV-system is installed. Mean values of all six combinations are displayed. It can be seen that the main savings already appear if a PV-system is installed. Additional savings by installing a storage system as stated in this work remain very limited. Taking current storage prices into account it results that using home-energy-storage systems is not economic at the moment (Sauer et al 2011). If using time-dependent tariffs the savings are on average higher especially with the variable tariffs scenario.

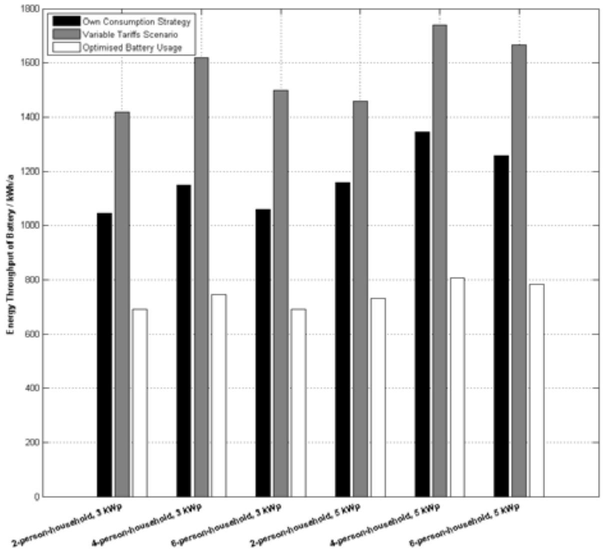

Figure 4: Energy Throughput of the Battery of Different Energy Management Strategies.

Table 1: Cost Savings.

	Savings Compared to a Household Without a PV-System	
	Constant Tariff	Time-Dependent Tariff
PV-System Without Battery	€ 511.48	€ 634.96
Own Consumption Strategy	€ 612.75	€ 689.04
Variable Tariffs Scenario	-	€ 779.47
Optimised Battery Usage	€ 525.35	€ 611.21

In figure 5 the self consumption rate is shown in dependence of the time resolution of the measurements of consumer load. It can be clearly seen that the self consumption rate decreases if measurements happen rarely. While the trend in the two-person-household is nearly stable until a resolution of 15 seconds the other combinations show already significant drops. The graphs visualise also that the load profile itself causes different gradients. It can be stated that the time resolution of the measurement systems and the working frequency of the energy management are very critical factors in calculating the self consumption rate. Comparing the results with data from literature shows the correct functionality and coincidence of the simulations (Braun et al 2010).

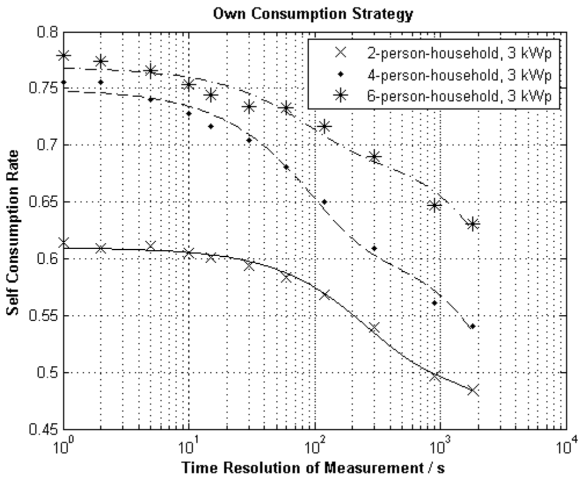

Figure 5: Self Consumption Rate in Dependence of Time Resolution.

Comparing the three energy management strategies it comes up that the own consumption scenario is the most efficient and therefore the most cost effective scenario. Nevertheless it has to be considered that by taking the results of the simulations into account such storage systems are not economically efficient at the moment.

Further steps and simulations regarding the grid functionality have to be executed to find optimal ways of grid assistance. The mentioned algorithms target the economic use of such systems especially for costumers and are not completely suitable for a stable grid operation especially when focusing on increased decentralized feed in of renewable energy sources.

6. CONCLUSION

In this paper different energy management strategies for grid interactive inverters with a battery storage are presented. For several configurations of PV systems and household loads self-consumption rates and a number of other characteristic numbers are calculated.

The energy management algorithms mentioned in this paper include:

- Increased own-consumption of electricity produced by the PV generators through storing excess energy and usage in times with lower solar irradiance.
- The use of the storage system for load adjustment in conjunction with time variable electricity tariffs.
- Optimised operation method for increasing the lifetime of the battery system.

For the simulations datasets of a real PV-power plant and three different households are used. Because of the high resolution of the data the simulations are carried out with a sample rate of 1s for one year of operation. Hence exact and practical representative results for the self-consumption rate could be reached.

The simulations showed that with such a system an increase of the self-consumption rate of more than 30 % compared to a normal photovoltaic system without storage is possible. As expected the own consumption strategy reaches the highest self-consumption rates at the most effective use of the battery storage. Using a special strategy when applying time variable tariffs cost savings of an average household of nearly 780 € per year are possible.

In this work special attention was paid to the influence of the resolution of power measurement to the resulting own-consumption rates which has been compared to known values in existing literature.

Due to the fast development in the sector of implementation of photovoltaics in electricity grids further simulations with other energy management strategies are the objective of further work.

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The load curves used in this project originated from the ADRES-CONCEPT database, therefore it should be stated from Adres (2011):

"The Data was generated in the research project "ADRES-CONCEPT" (EZ-IF: Development of concepts for ADRES – Autonomous Decentralized Regenerative Energy Systems, project no. 815 674). This project was funded by the Austrian Climate and Energy Fund and performed under the program "ENERGIE DER ZUKUNFT"."

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