Matching Circuit Topologies and Power Semiconductors for Energy Storage in Photovoltaic Systems

Due to recent changes of regulations and standards, energy storage is expected to become an increasingly interesting addition for photovoltaic installations, especially for systems below 30kW. A variety of circuit topologies can be used for the battery charger stage.

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These will require a different amount of semiconductors, voltage classes of the power devices, and in some cases the use of a transformer. Among the decisive factors for the circuit topology are the battery's electrical parameters and the required isolation between the battery bank and the inverter.

This article describes possible circuit configurations and presents the best matching power semiconductor devices in both, discrete and module forms, in order to achieve highly efficient and compact systems. In addition, it also discusses the battery technologies expected to be implemented in such storage systems, presenting their main advantages and drawbacks.

Introduction

Several countries in the world have adopted photovoltaic energy in their electrical generation matrix recently. This fact has been boosted majorly by the price decrease of the main components of a photovoltaic (PV) system, namely the photovoltaic modules and the PV inverter, combined with governmental programs. Good examples in Europe are Germany and Italy, where the implementation of new photovoltaic plants has been subsidized. Financing was done with the main intention of boosting non-polluting, renewable energy. A growing number of decentralized energy sources were an additional consequence.

Figure 1 illustrates the current situation in Germany with about 30GW of photovoltaic power installed. The figure presents the contribution of each energy source to the total grid power in a day of high solar irradiation and moderate temperatures. This represents the optimal conditions for photovoltaic cells. It can be observed how the installed PV plants cause an energy generation peak around midday. In order to avoid disturbances within the grid, the energy demand has to follow the same profile. Alternatively, the remaining energy sources have to reduce their production accordingly, returning to their normal values in the evening, when the PV production usually is decreased.

With the increase of PV systems and the majority of them connected to the mains, a natural consequence is the influence of solar irradiation on the amount of energy injected to the grid. This requires additional considerations within the grid management to avoid fluctuation of electrical parameters such as frequency and voltage. Those variations can be considered to occur over a year, from season to season, between day and night and even during the same day in case of cloudy weather.

Energy Storage Implementation

A typical photovoltaic system is composed of photovoltaic modules connected in series and/or parallel and a DC/AC inverter to properly convert the DC voltage to an AC grid level. In order to store the energy coming from the PV modules, a charge controller stage must be added to the system. This stage is responsible for the correct charging of the battery bank, as well as for recovering the stored energy back into the DC link.

Non-Isolated Charge Controllers

A simple way to implement an energy storage system for photovoltaic plants is depicted in Figure 2. The single-phase photovoltaic inverter is composed of a booster stage followed by a full-bridge inverter. Tied to the DC link, there is a charger stage, composed of two switches, two diodes and a filter inductor connected to the battery bank.

The voltage level of the DC link is kept constant by the booster stage and is expected to be higher than the voltage of the battery

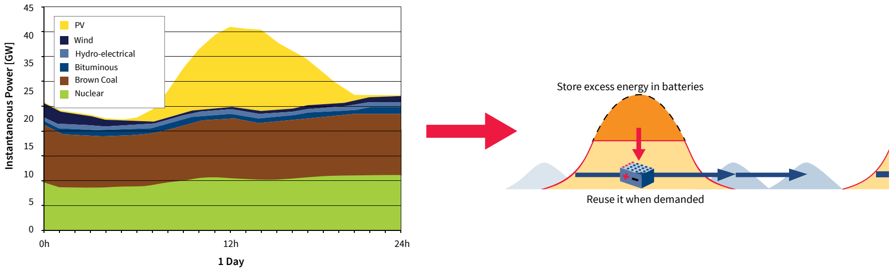

Figure 1: Contribution of PV power in Germany on a typical sunny day [1]. Peak generation storage and reuse [2].

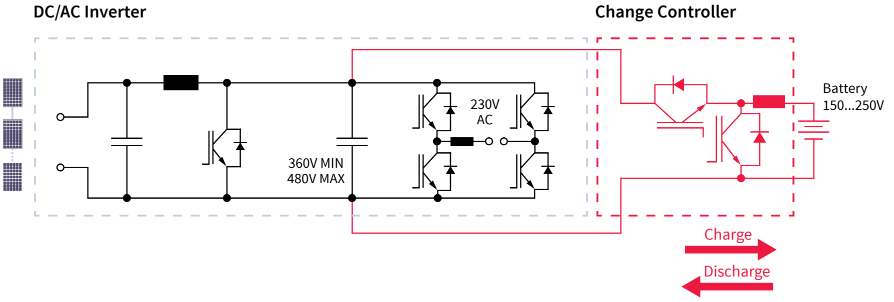

Figure 2: Non-isolated energy storage for photovoltaic systems.

bank. Common DC link values for single-phase systems are between 360V and 480V, while the voltage of the battery bank composed of several series-connected batteries is typically between 150V to 250V. Therefore, the controller stage will work as a step-down converter when charging the battery bank and as a step-up converter when transferring the energy from the batteries back into the DC link.

As main advantages of the configuration in Figure 2, a low amount of semiconductors is required and a high efficiency is achieved in both, charging and discharging paths. Figure 3 presents calculated efficiency values as a function of the charging current using a 50A 650V IGBT device from the TRENCHSTOP^{TM} 5 family [3]. A DC link voltage of 400V and a battery voltage of 150V have been assumed. As it can be seen, efficiency levels close to 98% during the battery charge at switching frequency of 20kHz are possible. At 40kHz, an efficiency of almost 97% is achievable. For the complete charge and discharge cycle, the resulting efficiency is obtained by multiplying charge- and discharge efficiency. This results in a total efficiency of 96% at 20kHz and 94% at 40kHz, not considering the batteries' resistive losses.

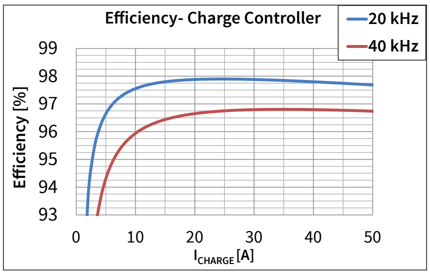

Figure 3: Efficiency results of a non-isolated charge controller based on IKW50N65H5 devices.

In case of three-phase systems, due to the fact that the DC link voltage can exceed 800V, power switches with blocking voltage of 1200V are required. The power module FF45R12W1J1_B11 [4] contains a half bridge based on CoolSiC^{TM} JFET technology, which can be used in a step-up/down topology allowing for bidirectional energy transfer. Additionally, this module permits adding value to the power design by using the SiC JFET channel during the freewheeling period. This enhancement can be achieved thanks to the bidirectional conduction capability of the SiC JFET.

Based on measurements, Figure 4 illustrates the predicted efficiency for a simulated 5kW three-phase storage inverter. It can be observed, that the efficiency achieved using the power module FF45R12W1J1_B11 is slightly higher than the one achieved using CoolSiC JFET combined with a thinQ!^{TM} SiC Schottky diode. Semiconductor losses are reduced by about 10%. In both cases, the efficiency for a 40kHz switching frequency and 650V DC link voltage exceeds 99% for almost all points of operation.

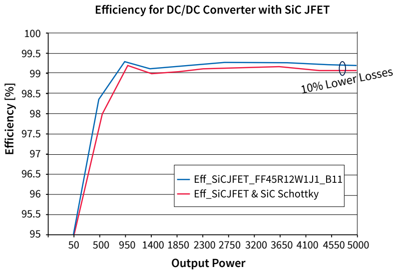

Figure 4: Efficiency results of a half-bridge topology with 1200V CoolSiC JFET power module.

Non-isolated topologies provide no galvanic isolation between the battery bank, the photovoltaic modules and the grid. For this reason, an extra circuitry is recommended in order to protect the battery bank from any overvoltage coming from the grid, for instance from lightning. This can be implemented for example by fuses connected to the positive and/or negative terminal of the battery bank, fast enough to disconnect it from the system. In addition, given the typical DC link voltage in both single- and three-phase systems, the non-isolated charge controllers require high-voltage batteries of 150V to 400V. The use of low voltage batteries would be technically feasible but the suboptimal modulation factor of the switches results in much lower system efficiency.

Isolated Charge Controllers

In order to overcome the drawbacks of the non-isolated charge controllers, a converter with a transformer providing an intrinsic galvanic isolation between the batteries and the other stages can be used. Moreover, by setting a suitable transformer ratio, it is possible to use low voltage batteries in the range of 12V to 96V.

Due to the high amount of semiconductors and the magnetic components, the isolated solution is expected to be more expensive and less efficient than the non-isolated charge controller. However, by using the latest IGBT technologies in association with soft-switching techniques, it is possible to reduce the semiconductor losses and thus obtain efficiency levels exceeding 95%.

The left part of Fig. 5 features the basic schematic of a zero voltage switching (ZVS) converter, where the two legs are driven using the phase-shift modulation technique. A similar converter is described in [5], including details of the modulation strategy.

The efficiency curve of a ZVS phase-shift converter is depicted on the right side of Figure 5. The use of additional output capacitors on the low-side IGBTs enables up to 0.8% efficiency increase of the converter. The reason for this is the fact, that the capacitors enable a faster extraction of the minority carriers inside the device during turn-off. This will shorten the tail current time of the IGBT, thus reducing the turn-off losses. Using this ZVS topology, the energy stored in the capacitors is not dissipated but returns to the circuit before the turn-on of the switches [6].

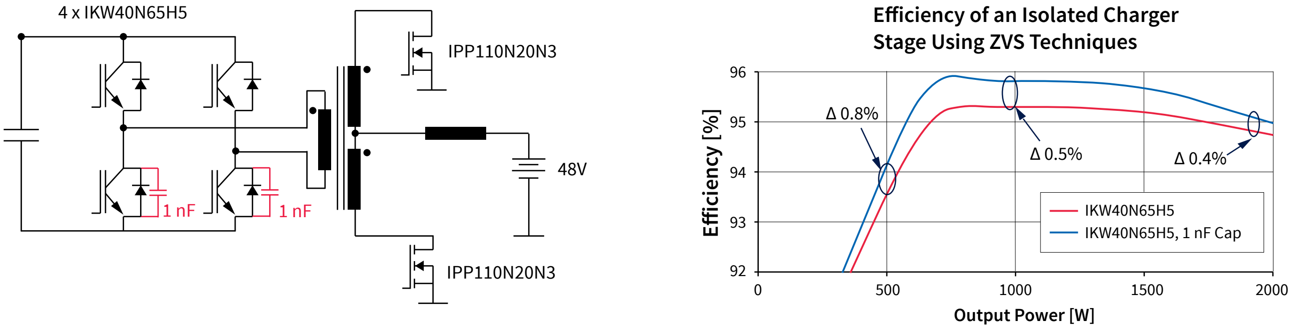

Figure 5: Schematic (left) and measured efficiency results (right) of a ZVS isolated charge controller, with and without the insertion of a 1 nF capacitor in parallel to the low-side IGBTs.

	Lead-Acid	Li-Ion (LiFePO4)
Specific energy	30–40 Wh/kg	100–265 Wh/kg
Energy density	60–75 Wh/l	250–730 Wh/L
Specific power	180 W/kg	250-340 W/kg
Energy/price	7 Wh/U$	2.5 Wh/U$
Price per kWh	140 U$	400 U$
Self-discharge rate (per month)	3% – 20%	15% @ 40°C
Cycle stability (80% DoD)	200–400 cycles	400-1200 cycles
Nominal cell voltage	2.1 V	3.2 V

Table 1: Electrical characteristics of Lead-Acid and Li-Ion batteries. [7]

Battery Technologies

Various battery technologies have been used in electrical systems as storage components. They differ from each other in terms of chemical and electrical properties. Table 1 summarizes the main electrical properties of two battery technologies, namely lead-acid and lithium-ion (Li-Ion). Due to technical and economic reasons, these are the main technologies which are expected to be used as storage elements in PV systems.

From the parameters energy/price and charge stability, it is possible to observe a clear trade-off between cost and lifetime of the batteries. Li-Ion batteries are supposed to be three times more expensive than lead-acid batteries with a comparable capacity. On the other hand, Li-Ion batteries can achieve up to 20 years of operation, in contrast to only five years expected for the lead-acid types. An alternative to increase the lifetime of lead-acid batteries is to oversize the storage capacity of the system. This would avoid a deep discharge of the batteries, however it would increase the cost of the overall installation.

In energy storage systems already commercially available, the choice for battery technology has developed towards Li-Ion [6][8]. Main factor for this decision is the longer lifetime offered by these batteries. Short battery lifetime in solar systems would lead to several substitutions of the batteries during the operation lifetime, thus increasing the cost of ownership. Additionally, in some countries the minimum battery lifetime is a requirement to apply for governmental subsidies. This is currently the case in Germany, where a minimum manufacturer warranty of seven years is demanded [9].

In order to achieve attractive battery lifetimes, a full battery discharge ought to be avoided, regardless of the battery technology in use. Depth of Discharge (DoD), normally given by battery manufacturers, sets how deeply the battery shall be discharged in order to warrant a given number of charging cycles. DoD for lithium Li-Ion batteries is usually 70-80% whereas for lead-acid only 50% are recommended [10].

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