Hybrid Photovoltaic Inverter for Smart Grids

T. Kupka and M. Patt

***Abstract*— This paper describes a bidirectional solar-battery-grid inverter, its principle and features as well as control functions and recent semiconductors which are used. The device is designed for smart grid applications, where the operator decides about a power and its direction for each active device. The proposed inverter is able to supply power grid by power and phase shift which are defined by superior logic. Or it can take required amount of power from the grid and store it in battery. Stored energy is used later for covering deficiency of solar energy. Solar cells are efficiently driven by MPP tracker and power balancing function ensures maximal usage of all sources.**

Keywords— **Solar inverter, Battery storage, Smart grid, H-bridge, Booster, MPPT, Power balancing**

I. Introduction

DIRECT solar energy transformation is worldwide spread type of subsidiary energy source. The most widely used system is a connection of string of photovoltaic panels and voltage inverter into the grid. The inverter feeds power network with maximal power, which could the panels currently produce. That leads solar plants to be unstable according to sun shine or clouds, similarly as wind plants depend on wind. Instability problem is often solved by power distribution management covering energy ripple by another source or connection to other network. However, there is growing need to have a solar plant with stable power output.

Another customers of solar industry are small house owners and families. There the need of having stable power source to cover as much their power consumption as possible is recently more and more requested. Currently used design concept of small solar-battery system combines PV and battery inverter and PV charger. Systems are set to cover the house consumption during the day and on the beginning of night. In the time when no energy is available, the consumption is covered by the grid. Example of a sunny day power distribution is shown on Figure 1.

Next step in solar-battery inverter is allowing distribution management to decide what power, its type and direction should be produced or spent by an inverter system. There, the battery could be charged from the grid in case of power surplus.

Tomas Kupka, is with the Department of Electric Drivers and Traction, Faculty of Electrical Engineering, Czech Technical University in Prague, Prague, CZ-16627, Czech Republic. (e-mail: kupkato3@fel.cvut.cz).

Michael Patt, is with Technologienetzwerk Allgäu, Memmingen, D-87700, Germany. (e-mail: michael.patt@tn-allgaeu.de).

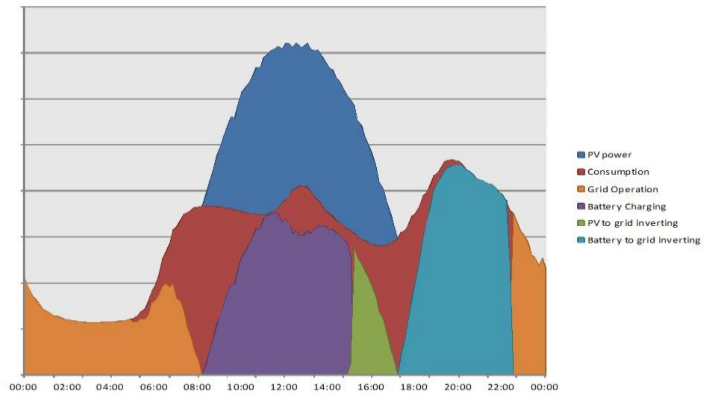

Figure 1: One-day power distribution

II. Block Diagram

The device consists of three active power parts: PV booster, battery buck/boost converter and grid inverter/PFC and control parts: DSP, MUC and boost-driver. Block diagram is shown on Figure 2.

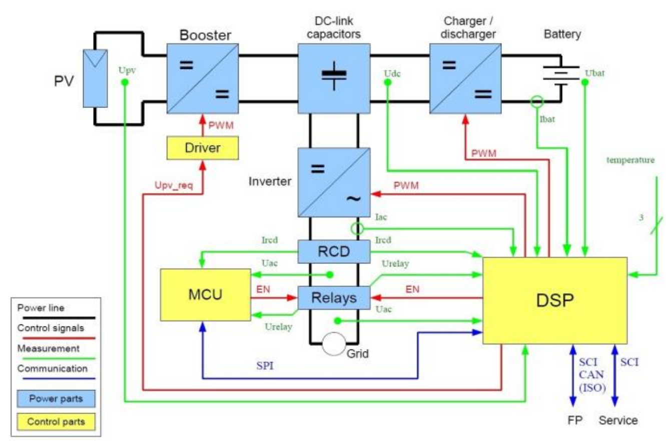

Fig.2. Block diagram

Power parts are connected together or with the ambient by passive power devices: DC-link capacitors, relays, filters and current measurement. Controlling chips, voltage measurements, communication circuits, auxiliary power supply and interconnections represent low power part of system. The most important power blocks will be described below.

A. *Photovoltaic booster*

The base of this block is one of standard types of DC-DC step-up converter. Its propose is to convert solar voltage to higher DC-link voltage. Value of input voltage is controlled by analog PI regulator according to required value coming out of central logic (DSP). That function allows Maximal Power Point Tracker (MPPT) to find and set correct operating point.

Two-phase quasi-resonant transition mode construction with interleaved function allows booster to be small and high efficient. Peak efficiency reaches 98.8% in dependence on power and input voltage as shown on Figure 3.

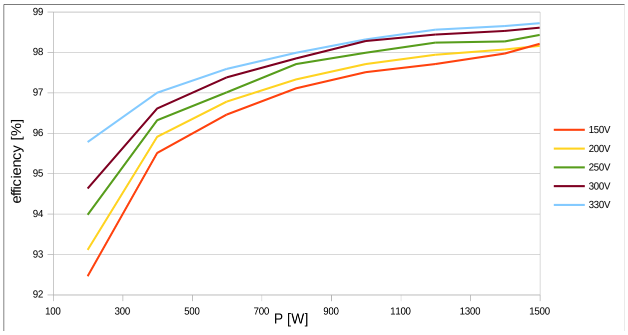

Fig. 3. Efficiency of quasi-resonant PV booster

Smart controlling allows to reach also a high partial load efficiency, because one channel is switched off. The booster works in resonant mode since the PV-input voltage is lower than half of the DC-link voltage as shown on Figure 4, compared to Figure 5 (green – Uds [100V/div]; red – Ugs [10V/div]; violet – current; Udc = 400V).

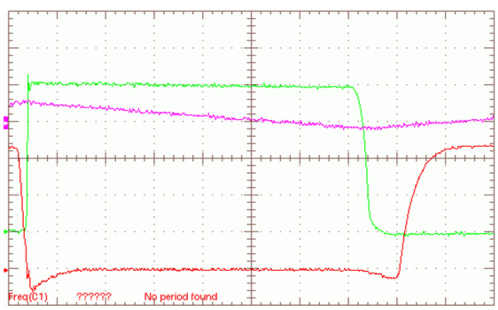

Fig. 4. Resonant switching (Upv=230V)

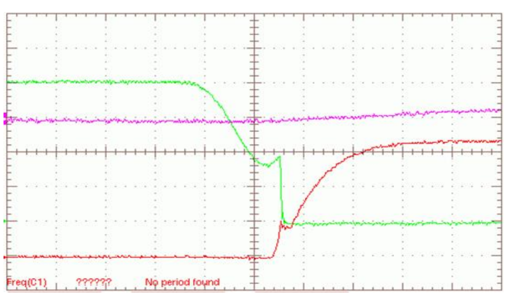

Fig. 5. Non-resonant switching (Upv=356V)

The booster consists of two MOSFETs IPP60R099CPA and two diodes IDP45E60. Both chokes have ferrite cores and additional auxiliary windings for zero-cross detection.

B. *Battery buck/boost inverter*

This part is responsible for charging and discharging the battery. It's a single leg bidirectional DC-DC converter. Due to the bi-directionality of the converter there are no MOSFETs suitable, because it works in continuous conduction mode (CCM). Discontinuous conduction mode (DCM) is also possible, but it makes the controlling effort higher. The IKW40N65F5 IGBT have been used for the battery buck/boost. They are reaching a peak-efficiency of 95,8 % with a 100V battery and a 390V DC-link voltage. The battery voltage has a high influence on the efficiency like a system related parameter. A 100V battery is comparable with a low voltage PFC. The measured efficiency is shown in Figure 6.

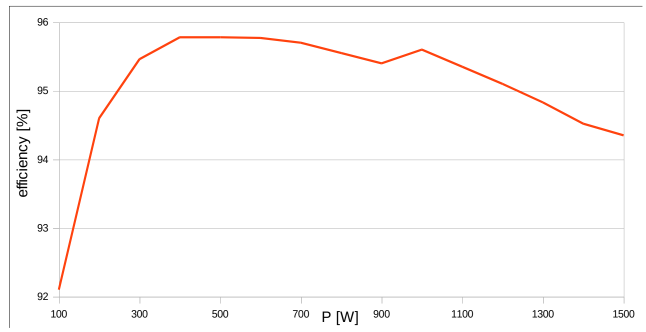

Fig. 6. Battery chopper efficiency for DC-link voltage 390V

C. *Grid inverter/PFC*

Grid converter is designed as a bidirectional H-bridge inverter with reactive power capability. Optimized high switching frequency provides high efficiency and low dimensions.

There are no MOSFETs suitable if the reactive power is produced by fundamental and if CCM is used. Otherwise the load current commutes from its substart-diode. Even irradiated MOSFETs with fast body-diode have from recent experiences not enough performance because the switching losses are too high. Therefore the IKW40N65F5 IGBTs have been used in H-configuration with bidirectional PWM switching pattern.

D. *Common power parts*

The rest of power circuit consists of intermediate capacitance, filters, relays, current measurement and interconnections. The DC-Link capacitor current is independent from the reactive power. The complete RMS current is equal to the grid current. The part with double line frequency depends on the modulation index and this depends on the relation between grid voltage and DC-link voltage. Filters make the device free of EMI emissions and a double relay ensures safety of the system, device and operators.

III. CONTROL SYSTEM

Major controlling function is executed by Digital Signal Processor TMS320F2808 from Texas Instruments company. Embedded software contains low hardware controlling functions and measurements as well as higher logic and communication. Firmware calibration and specific settings are stored in a programmable memory. Secondary controller (MCU) is responsible for redundant grid observation and start-up relay check. It communicates with DSP by SPI bus as a slave, but connecting and disconnecting the relay is autonomic.

DSP is fast and powerful enough to generate and control PWM signals for two inverters, to measure currents, voltages and temperatures including a true RMS measurement of AC values, to keep solar cells in optimal working point by MPPT, to do a simple battery management and to communicate with slave MCU and superior logic. Additionally, software is adjusted to be able to work automatically in one of modes specified in Table 1. Due to this, supervisor need only to set the mode and power and send start command. All other function (MPPT, battery management, power balancing, …) are managed by DSP.

Table 1. Specified woking modes

No.	Mode	Power direction	Set values	Functions
1	Photovoltaic inverter	PV → Grid	ps	MPPT
2	Battery inverter	Battery → Grid	P, ps	BM
3	Grid charger	Grid → Battery	P	BM
4	Photovoltaic charger	PV → battery	P	MPPT, BM
5	Hybrid inverter	PV, Battery → Grid or PV → Grid, Battery	P, ps	MPPT, BM, PB
6	Hybrid charger	Grid → Battery or PV, Grid → Battery	P	MPPT, BM, PB

P – power MPPT – maximal power point tracker
ps – phase shift BM – battery management
PB – power balancing

There are three possibilities of controlling the inverter. First two are designed for real operation. It is serial interface (SCI) and CAN bus. Both are optically separated. The thirds serial connection is used for production and service proposes.

A. *Maximal power point tracker (MPPT)*

Maximal power of photovoltaic cell depends on its voltage according to sun shine intensity. There are several algorithms for MPPT implementation (Perturb and Observe, Incremental conductance, etc.). Described inverter uses power derivation feature of photovoltaic panel as is shown on Figure 7. MPPT function works with power derivation similarly to standard Incremental Conductance Algorithm.

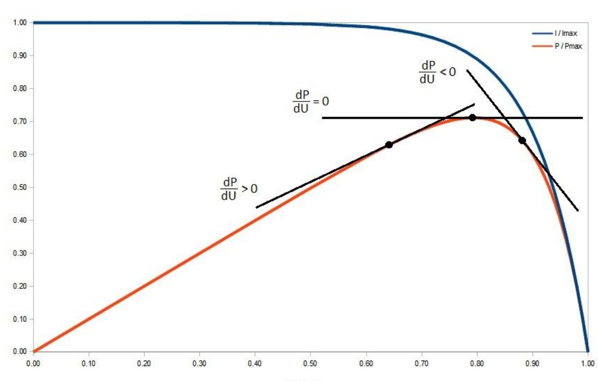

Fig. 7. Power and current to voltage dependance of solar cell

B. *Power balancing*

Base of power balancing system is MPPT, battery management and required power limiter. Maximal power point tracker keeps solar cell working in efficient state, battery charging management decreases the power if the battery is getting full or empty as well as power limiter doesn't allow exceeding required power. These all function together with AC voltage and temperature derater stabilizes the system in simple two-direction modes (1, 2, 3 and 4). For three-direction modes (5 and 6) is necessary to implement additional balancing functions hinted in Table 2.

Table 2. Power balancing logic background

	Priority	4	3	3	2	1
	Event	Normal operation	BM power limitation	Required power exceeded	AC voltage limit	Temperature limit
PV inverter	Booster	MPPT	-	Control P-required	Control P-AC limit	Control P-temp. limit
	Battery bridge	-	-	-	-	-
	Grid bridge	Follow PV	-	Follow PV	Follow PV	follow PV
Bat. inverter (discharging)	Booster	-	-	-	-	-
	Battery bridge	Control P-required	Control P-BM limit	Control P-required	Control P-AC limit	Control P-temp. limit
	Grid bridge	Follow Battery	Follow Battery	Follow Battery	Follow Battery	Follow Battery
Grid Charger (charging)	Booster	-	-	-	-	-
	Battery bridge	Follow Grid	Follow Grid	Follow Grid	Follow Grid	Follow Grid
	Grid bridge	Control P-required	Control P-BM limit	Control P-required	Control P-AC limit	Control P-temp. limit
PV Charger (charging)	Booster	MPPT	Control P-BM limit	Control P-required	Control P-AC limit	Control P-temp. limit
	Battery bridge	Follow PV	Follow PV	Follow PV	Follow PV	Follow PV
	Grid bridge	-	-	-	-	-
Hybrid Inverter	Booster	MPPT	MPPT	MPPT or Control P-required (if battery is full)	MPPT or Control P-AC limit (if battery is full)	MPPT or Control P-temp. limit (if battery is full)
	Battery bridge	Charge (if Ppv > P-required), Discharge (if Ppv < P-required)	Decrease P (if discharging), Increase P (if charging)	Decrease P (if discharging), Increase P (if charging)	Decrease P (if discharging), Increase P (if charging)	Decrease P (if discharging), Increase P (if charging)
	Grid bridge	Follow PV and Battery	Follow PV and Battery	Follow PV and Battery	Follow PV and Battery	Follow PV and Battery
Hybrid Charger	Booster	MPPT	Decrease P	Decrease P	Decrease P	Decrease P
	Battery bridge	Follow PV and Battery	Follow PV and Battery	Follow PV and Battery	Follow PV and Battery	Follow PV and Battery
	Grid bridge	Control P-required	Control P-required, Decrease P (if PV disabled)	Control P-required	Control P-required, Decrease P (if PV disabled)	Control P-required, Decrease P (if PV disabled)

IV. CONCLUSION

The paper described one of recent solar inverters, its design, features and technology. Maximal power point tracking and power balancing problematic was mentioned too.

Further development will be focused to use the inverter in fully island mode. That device could be used like power source in places without energy connection or like an emergency power supply in power line defection.

ACKNOWLEDGMENT

The study is selected from *International Symposium on Sustainable Development*, ISSD 2013.

REFERENCES

[1] M.Patt,(2008). Eigenschaften vontransformatorlosen Photovoltaikwechselrichtern. Proceedings VDE Kongress München

[2] M.A.Elgendy, B.Zahawi, & D.J.Atkinson, (2012). Low Cost MPPT Algorithms for PV Application: PV Pumping Case Study. Newcastle University presentation

BIOGRAPHIES

Tomas Kupka received the master degree in electrical engineering from the Brno University of Technology, Czech Republic, in 2006. Presently he continues education the Ph.D. degree in on Czech Technical University in Prague, Czech Republic, with planed graduation in 2015. He also works in design-house company Finepower GmbH in Ismaning, Germany. His domains are controlling systems for power application.

Michael Patt received the doctor degree in power electronic from the Helmut Schmidt University in Hamburg, Germany. Since 2012 he holds a professorship on Technologienetzwerk Allgäu, Memingen, Germany. The scale of his interest consists of power electronic for voltage and current inverters in various applications.