Multifunctional PV battery systems for industrial applications

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ABSTRACT

Power quality and reliability are two very important factors in electrical power supply, particularly for specific branches of industry. Multifunctional PV battery systems can improve power quality, substitute uninterruptible power supply systems, and can offer additional services such as energy management and peak shaving. This article presents the results of an analysis of possible services under current German conditions and the measurement results of laboratory tests and a pilot demonstration.

Introduction

Given the worldwide efforts being made to give priority to renewable energy, there is a wide range of potential applications for multifunctional PV inverters to create grid areas with a high power quality, e.g. for industry, and integrate these systems effectively in the electrical power system operation and energy supply.

The objective of the 'Multifunctional Photovoltaic Inverter' (Multi-PV) research and development project was to develop a multifunctional PV inverter that connects not only the PV modules but also a battery unit [1]. In addition to feeding in the active power from PV to the public grid, this type of inverter is also intended to be used to improve the local power quality and, in combination with battery storage, ensure an uninterrupted power supply for critical loads in industrial networks. Another goal is to use the battery storage for energy management purposes, such as peak shaving, and to provide services for network operation, such as balancing power.

Figure 1. Industrial site of Hübner GmbH in Kassel (courtesy of ISET).

ISET e.V. and SMA Solar Technology AG (SMA) in Kassel, Germany investigated the general conditions for the operation of multifunctional PV inverters (from technological and economic perspectives) and developed the corresponding inverter technology. The 100kVA prototype is under operation at the industrial site of the project partner Hübner GmbH (see Fig. 1) demonstrating the developed functionalities.

Fig. 2 gives a schematic overview of the Multi-PV concept. In addition to the PV generator, a battery is connected via the DC/DC converter to the DC link of the PV inverter. Industrial loads with additional services, such as improved power quality, are decoupled from other loads and the public grid by an inductor as well as a fast circuit-breaker. The inductor is necessary to locally improve the power quality and provide uninterruptible power

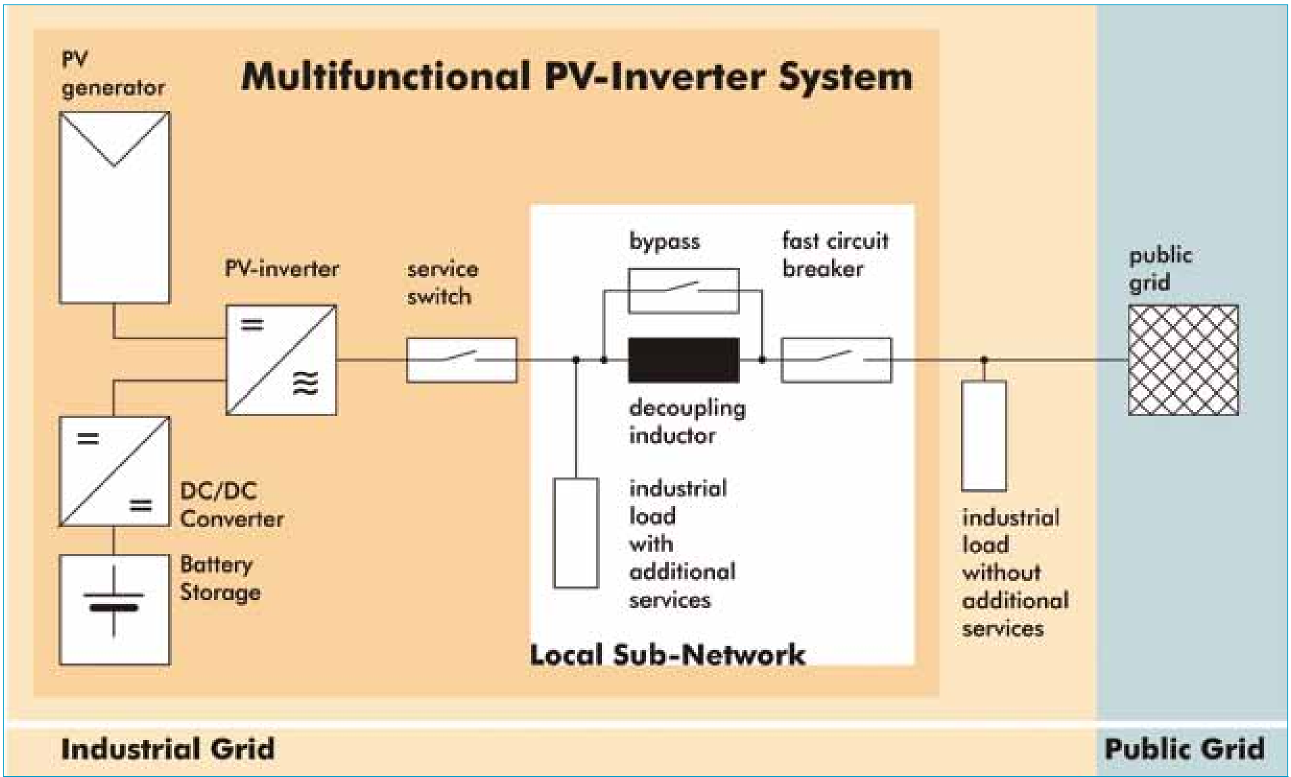

Figure 2. Schematic of a Multi-PV system at an industrial site [2].

supply to critical industrial loads. These new components (battery, decoupling inductance, and fast circuit-breaker) enhance the capabilities of a standard PV inverter to a multifunctional device with many possibilities to provide additional services.

This paper presents the results of an investigation of the economic potential of multifunctional inverters under German conditions, such as feed-in tariff, European Energy Exchange (EEX), markets for ancillary services and power supply tariffs. In addition, it provides experiences from the laboratory tests and prototype operation at the industrial partner.

Economic potential

The services given in Table 1 can be considered in an economic analysis with their respective sources of benefits. Different investigations determined the optimal power dispatch to achieve maximum economic profit with the Multi-PV system [2-6]. Three exemplary companies (C1, C2 and C3) with their respective load profiles are analyzed. The optimal dispatch results and sensitivity analyses show that the achieved profit mainly depends on the characteristics of the load profile itself. As one example, the optimized power dispatch schedule is given in Fig. 4 for C1 in the year 2007 taking into account peak-shaving, trading on the day-ahead market, and participating on tertiary balancing services markets.

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The possible services are analyzed in more detail in [4] limiting them to the economic interesting services. It can be seen that the greatest profits result from restricting the system to peak shaving and the UPS functionality.

Fig. 3 shows the additional profit from peak shaving including UPS functionality by the Multi-PV system for company C1 depending on the battery capacity and the capacity price for power supply. The colour of the map indicates the additional annual benefit (compared to a conventional PV system + UPS unit) and the black dotted line marks the maximum additional benefit at a given capacity price. In this example, the investment costs for the battery are assumed to be 95 €/kWh battery capacity and 110 €/kW for the DC/DC-converter and the disconnection unit. Due to there being only 22-24 battery cycles per year, the lifetime for all components was calculated as 20 years.

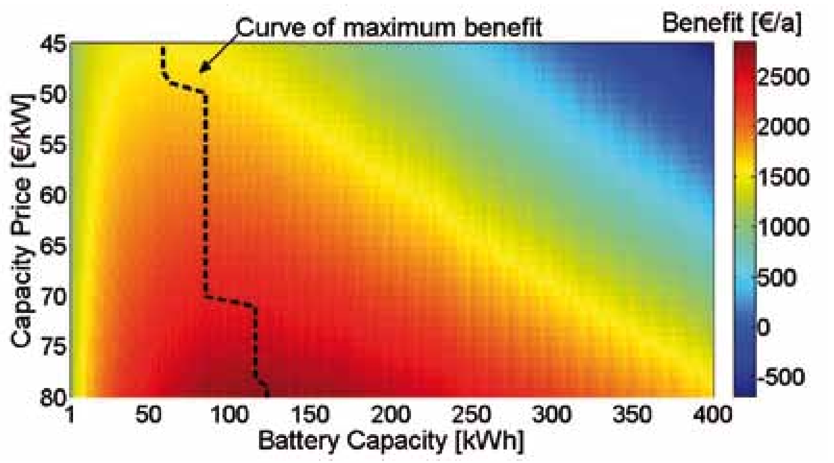


Figure 3. Additional profit for company C1 depending on the batteries' capacity and the capacity price for power supply [4].

Table 2 gives an overview of the range of the maximum profit provided by the Multi-PV system for each of the three investigated companies with the capacity price in the range of 45-80 €/kW per annum. The additional profit provided by the Multi-PV system with peak shaving and UPS functionality mainly depends on the characteristics of the companies' load profile. The less common, the shorter and the higher the load peaks are, the less energy is required from the battery. So, the battery size can be smaller.

Sensitivity analyses show that the additional investment costs (due to battery and DC-DC-converter) only have a minor influence on the profit because of the generally small component costs.

A comparison of the integrated Multi-PV concept (only one inverter for PV modules and battery) with the modular concept (two separate inverters for PV modules and battery) shows that the integrated concept is more profitable (saving one DC/DC-converter) despite having the constraint of only one inverter.

Experiences from laboratory and prototype operation

During the project run time, a laboratory sample (Fig. 5) and a prototype unit were developed and tested by ISET and SMA. While SMA is responsible for the hardware layout of the laboratory sample, the control

Services	Benefits by
Improvement of local power quality	Substitution of conventional devices or increased power quality
Compensation of reactive power	Substitution of conventional devices or reduction of reactive power purchase costs [3]
Uninterruptible power supply (UPS)	Substitution of conventional devices or increased reliability
Peak shaving	Reduction of capacity costs
Energy management	Reduction of energy costs
Participation on balancing services markets	Market prices for primary control, secondary control and tertiary reserve
Power trading	Market prices on day-ahead or intraday-market of the EEX
Ancillary services	Payments for providing active and reactive power control to the network operator

Table 1. Possible services by Multi-PV and their respective sources of benefit [4].

	C 1	C 2	C 3
Range of optimal battery size [kWh]	59-123	45	46-51
Additional Annual Revenues [/a]	3,360-5,383	6,504-10,004	3,145-4,101
Additional Annual Costs [/a]	1,805-2,544	1,631	1,699-1,755
Additional Annual Profit [/a]	1,555-2,839	4,873-8,373	1,446-2,346

Table 2. Maximum possible profit provided by Multi-PV under the aforementioned framework conditions [4].

of the inverter is realized with a rapid-control-prototyping system [7] by ISET. Experience from testing the laboratory sample is applied to the development process of the prototype unit. In regard to a serial product, the prototype unit is completely engineered by SMA.

Taking into account the principle of decoupled sub-networks [9] used for local voltage control and UPS functionality, it is not possible to combine all of the functionalities described in Table 1 together. Table 3 presents an overview of possible combinations of the different functionalities.

Laboratory measurement results

Laboratory tests concerning local power quality improvements are carried out with the laboratory sample in ISET's DeMoTec. For these experiments a Spitzenberger & Spies network simulator with a nominal apparent power of 90kVA was used to influence the grid systematically and in a reproducible fashion. The following results of the laboratory tests show the influence of the decoupling inductor on

- steady-state voltage variations,
- transient voltage variations, and
- voltage quality.

Steady-state voltage variations

Steady-state voltage variations of the grid voltage are compensated only for loads in the sub-network through an advanced control algorithm and the application of the decoupling inductor. The voltage in the sub-network is controlled to a pre-defined set-point by injection of reactive power.

Function	With Decoupling Inductor	Without Decoupling Inductor
Feed-in of PV energy	yes	yes
Local PQ Improvement	yes	no
UPS Functionality	yes	yes/no*
Provision of Control Energy	yes	yes
Peak Shaving	yes	yes
Reactive Power Supply/ Compensation at PCC**	no	yes
Harmonics Compensation at PCC	no	yes

Table 3. Possible functionality depending on the system configuration, modified from [7] (* = dependent on the UPS classification according to EN 62040-3; ** = Point of Common Coupling).

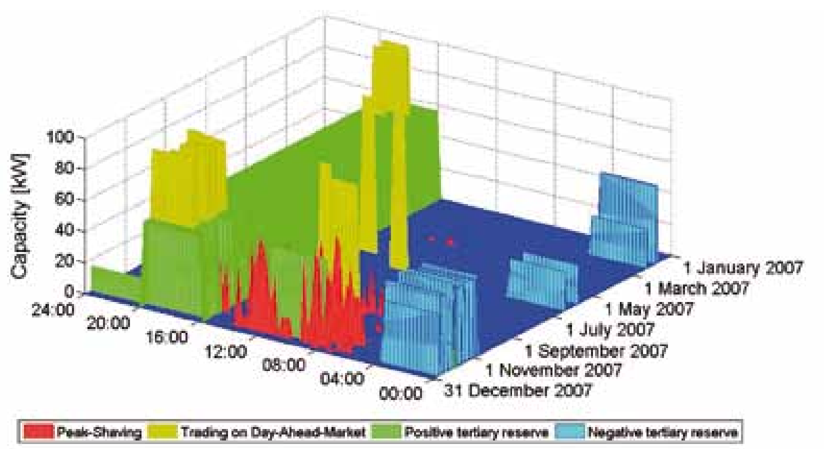
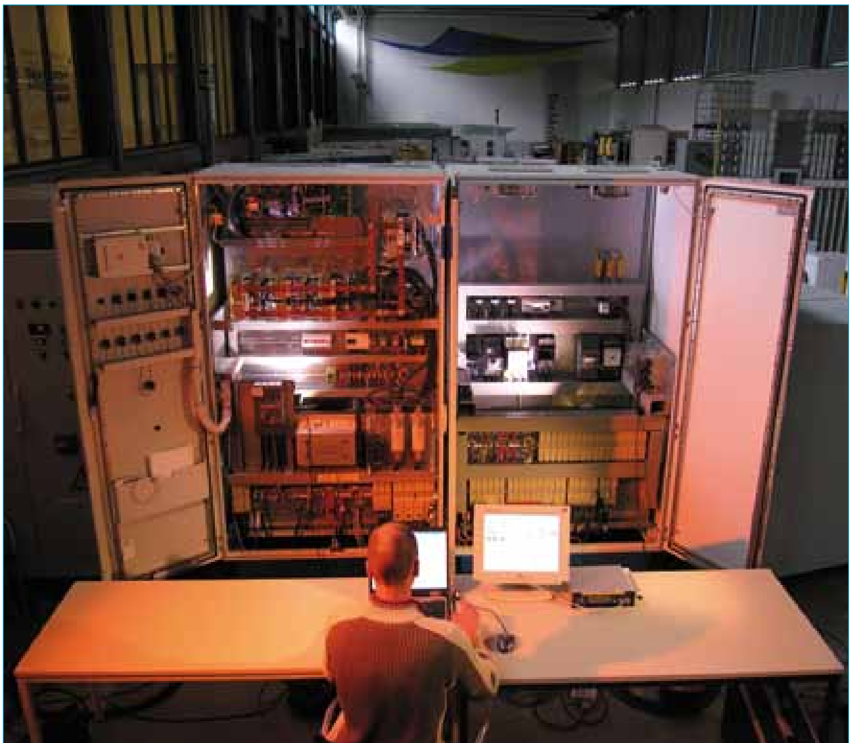


Figure 4. Optimized power dispatch schedule for the exemplary company C1 [4].



Courtesy: ISET.

Figure 5. Laboratory sample of the Multi-PV at ISET e.V.'s DeMoTec.

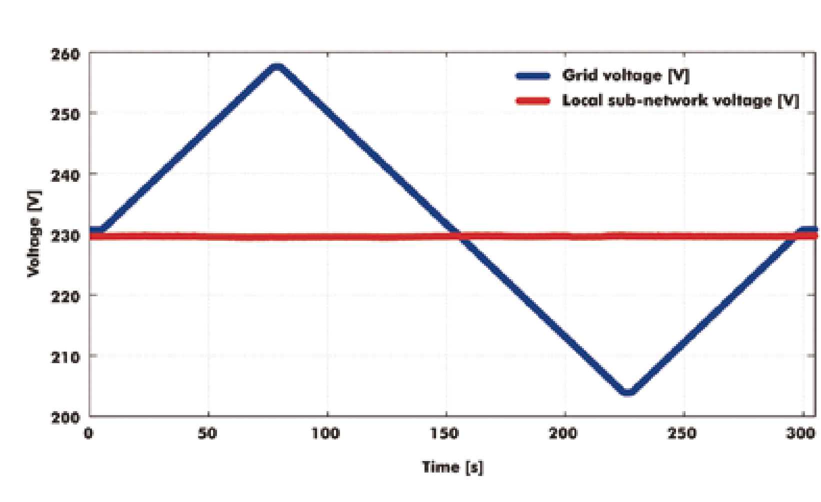


Figure 6. Measured sub-network voltage during an applied grid voltage ramp of $230V_{RMS} \pm 10\%$ [2].

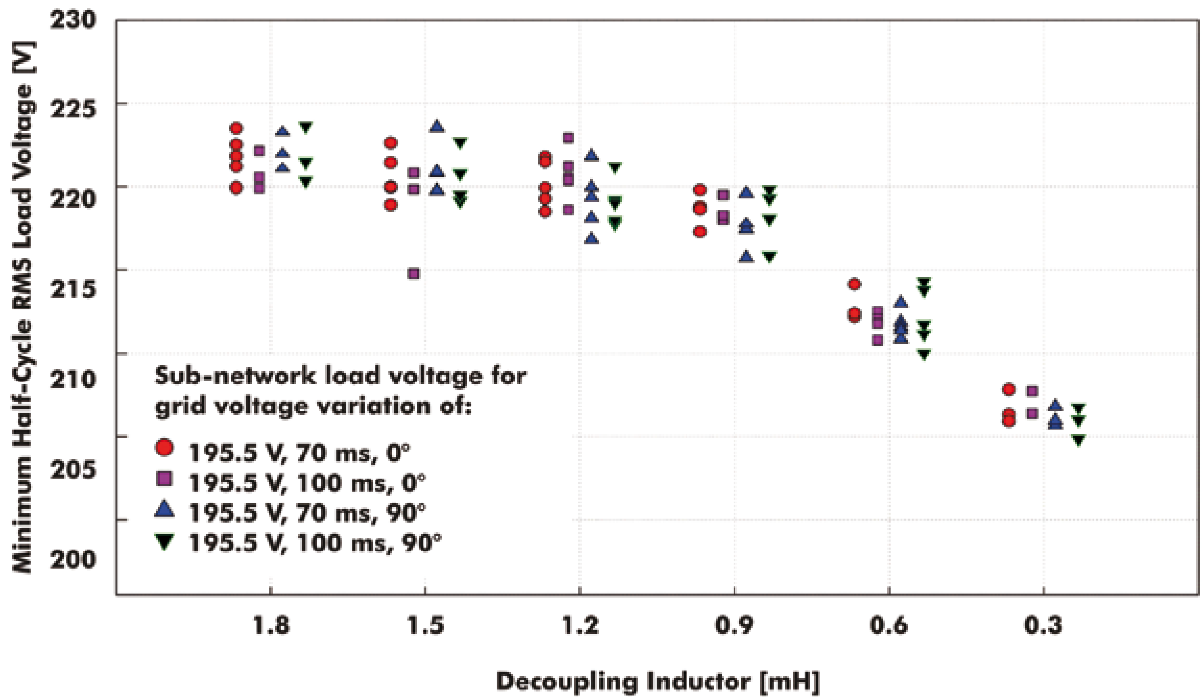


Figure 7. Reaction of load phase 3 to different three-phase voltage dips with 85% remaining nominal voltage for several decoupling inductors [2].

Measurement results of the laboratory sample for a grid voltage variation of $230V_{RMS}$ ± 10% are shown in Fig. 6. The sub-network voltage is controlled to the set-point of 230V.

Transient voltage variations

Voltage dips in the grid are damped for sensitive loads in the local sub-network through injection of an additional reactive current by the inverter. Depending on several parameters, e.g. the size of the decoupling inductor, the damping factor capability can vary. Measurement results for several types of voltage dips are exemplarily shown in Fig. 7.

Allowing a voltage deviation of ± 10% at most, a decoupling inductor of 0.6mH is sufficient for the considered voltage dips. If deeper dips in the network voltage occur and the operating mode has to be switched to a UPS service, the chosen value of the decoupling inductor must be tested to comply with the classification according to EN 62040-3 [10].

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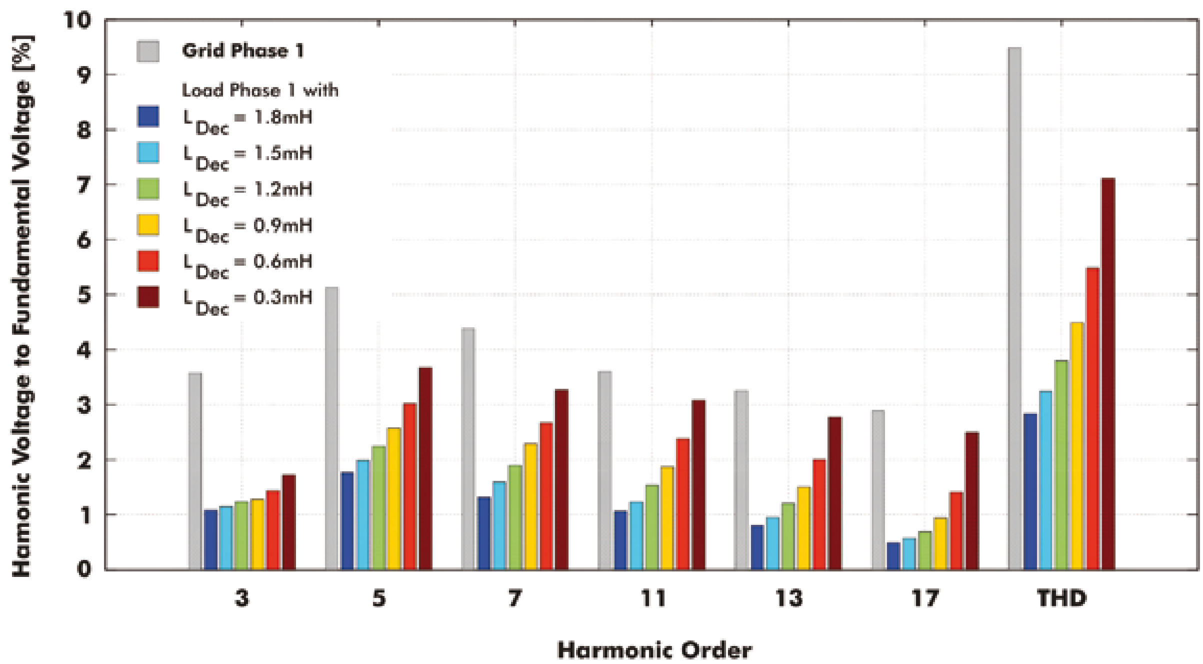

Figure 8. Harmonic reduction for various decoupling inductors where P_{MPV} = 50kW and $P_{sub-net}$ = 100kW [2].

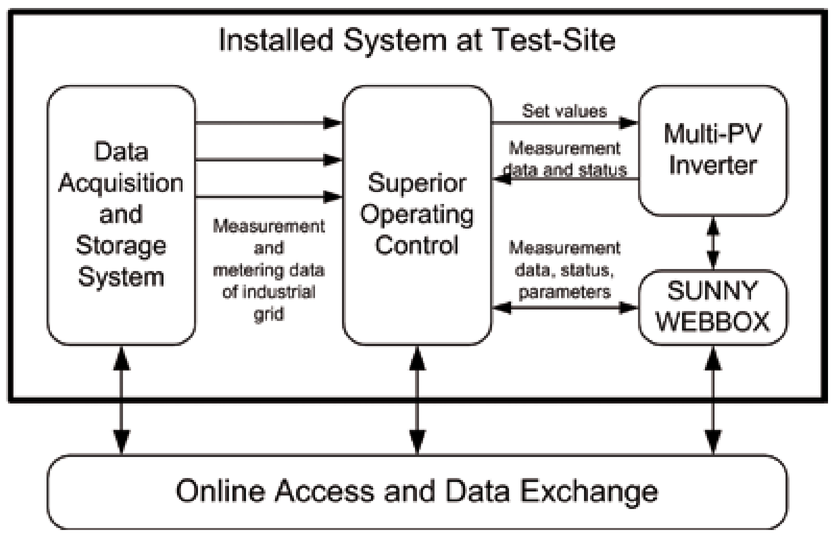

Figure 9. Assembly of the Multi-PV prototype system with data acquisition system, superior operating control and Multi-PV inverter [8].

Voltage quality improvement

Powerful motors, fast-changing loads or welding machines can affect voltage quality especially in industrial environments. An improvement of voltage quality for loads in the sub-network is achieved. The behaviour of the Multi-PV is tested for typical odd harmonics (3rd, 5th, 7th, 11th, 13th and 17th) with different amplitudes. Measurement results are given in Fig. 8.

The grid is disturbed by a total harmonic distortion (THD) of 9.5 %. Depending on the size of the decoupling inductor, the THD value in the sub-network is improved to 7.11 % at minimum and 2.83 % at maximum. This means that rather than a voltage quality of class 3 of DIN EN 61000-2-4, the quality is improved to class 2 (for decoupling inductors from 0.3mH to 1.5mH) and to class 1 for a decoupling inductor of 1.8mH.

Prototype operation in industrial environments

Since December 2008, the developed prototype system runs at the test site of Hübner GmbH in Kassel. The following sections present the general configuration and first test results of the application of reactive power compensation.

General configuration

The schematic in Fig. 9 shows the interaction of the used components in the prototype system. The Multi-PV inverter has several basic operating modes, e.g. MPP-Tracking, reactive power injection and UPS functionality. The system is managed by the Superior Operating Control and is based on the measurement and metering data of the Data Acquisition System. It defines the operating times of the system, oversees the battery management and calculates appropriate set-point values for additional functionalities as reactive power compensation and peak shaving and provides them to the Multi-PV inverter.

Reactive power compensation

The operator of an industrial grid has to keep a certain power factor at the Point of Common Coupling (PCC) against the utility to avoid paying for reactive energy. If the reactive power compensation demand and the solar radiation profile are known, the power compensation can be partly taken over or substituted completely by the Multi-PV inverter system.

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A Matlab/Simulink model of the assembly shown in Fig. 9 is developed to test the used control algorithm for reactive power compensation with measurement data of the test site.

Figure 10 shows simulation results of the 15-minute average power factor over a whole day (28th April 2009) with and without reactive power compensation. It can clearly be seen that the average power factor at the PCC without reactive power compensation is smaller than the desired set-point of 0.95. Using the reactive power compensation operating mode, the average power factor is limited reliably.

The algorithm is implemented to the superior operating control of the prototyping system. Measurement results of the 15-minute average power factor from 14th July 2009 are shown in Fig. 11.

The measurement results confirm the simulation results; the average power factor is limited reliably to the given set-point of 0.95. This proves the feasibility of reactive power compensation with a PV inverter in an industrial environment. Limits resulting from the parallel operation of PV-injection and reactive power compensation – for example, a limitation of the apparent power reserve – are considered by the developed control algorithm.

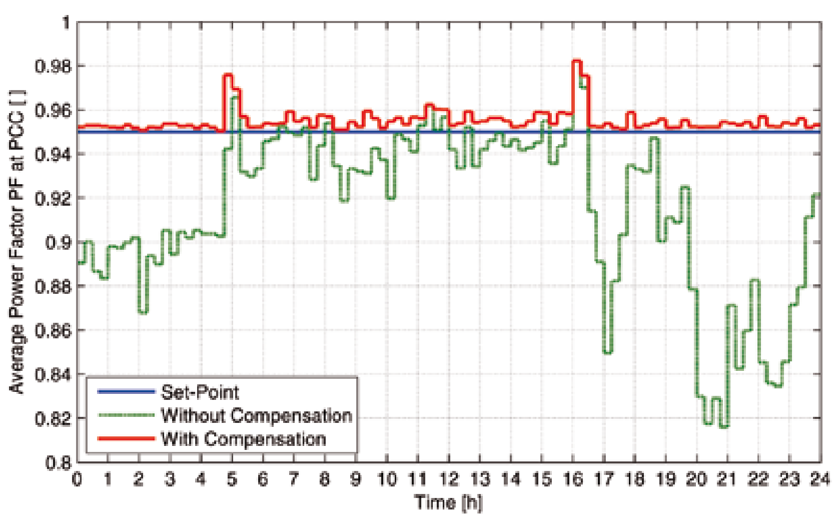

Figure 10. Simulation results of the power factor at the PCC with and without reactive power compensation using measurement data from 28th April 2009.

Conclusions

The results of this investigation show that the developed Multi-PV system can provide additional economic profits for companies. Case studies have been performed for three different industrial sites, and results show that individual conditions strongly influence the potential profitability. Most interesting

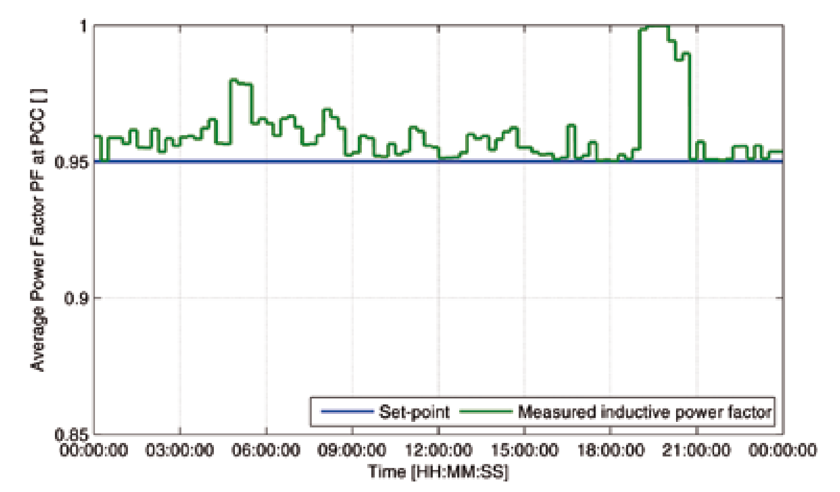

Figure 11. Measurement results of the average power factor of the test site from 14th July 2009.

among these conditions are peak shaving and uninterruptible power supply, while functions such as participation in power exchange markets and balancing services markets may be of interest in the future when the legal framework allows more flexible participation than it does currently. Finally, the improvement of the local power quality and reactive power compensation can also be beneficial.

Technical feasibility of additional functionalities is proved by measurements in the laboratory and at Hübner's test site. Power Quality is improved in the case of steady-state and transient voltage variations as well as for voltage quality. Reactive power compensation is demonstrated under real terms in an industrial environment.

In summary, it can be said that the Multi-PV system is an innovative approach. It integrates a photovoltaic system within the emergency power supply strategy of companies and in many cases, the reliability and duration of the uninterruptible and emergency power supply can be increased significantly if the local photovoltaic power generation and the larger battery size are taken into account. The integration of photovoltaic-based local power generation and the emergency power supply allows the use of only one inverter instead of two separate ones. Using one multifunctional inverter in an integrated system can considerably reduce investment costs and increase the overall profitability of the investment.

Acknowledgement

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References

[1] Reekers, J., Vogel, M., Jahn, J., Landau, M. & Strauß, P. 2006, "Multifunktionale Photovoltaik-Wechselrichter – Optimierung von Industrienetzen und öffentlichen Netzen", *11th Kasseler Symposium Energy Systems Technology*, Kassel, Germany.

[2] Geibel, D. 2008, "Power Quality Improvement of Electrical Sub-Networks with multifunctional PV-Inverters for Industrial Customers", *23rd EU PVSEC*, Valencia, Spain.

[3] Braun, M. 2007, "Reactive Power Supplied by PV-Inverters - Cost-Benefit-Analysis", *22nd EU PVSEC*, Milan, Italy.

[4] Braun, M., Stetz, T. 2008, "Multifunctional Photovoltaic Inverters - Economic Potential of Grid-Connected Multifunctional PV-Battery-Systems in Industrial Environments", *23rd EU PVSEC*, Valencia, Spain.

[5] Prior, J. 2006, "Wirtschaftliche Optimierung des Einsatzes von multifunktionalen Wechselrichtern", Diploma-Thesis, University of Kassel, written at ISET.

[6] Stetz, T. 2008, "Optimiertes Spitzenlastmanagement für multifunktionale PV-Wechselrichter", Diploma-Thesis, University of Applied Sciences, Darmstadt, written at ISET.

[7] Geibel, D., Jahn, J. & Juchem, R. 2007, "Simulation model based control development for a multifunctional PV-inverter", *12th European Conference on Power Electronics and Applications*, Aalborg, Denmark.

[8] Geibel, D. "Multifunctional Photovoltaic Inverter Systems – Energy Management and Improvement of Power Quality and Reliability in Industrial Environments", to be presented at *IEEE Energy Conversion Congress and Exposition 2009*, San Jose, California, USA.

[9] Engler, A. & Jahn, J. 2007, "Inductive Decoupling of Low Voltage Sub-Networks, 9th International Conference on Electrical Power Quality and Utilization (EPQU)", Barcelona, Spain.

[10] Geibel, D. & Hardt, C. "Improvement of Power Quality and Reliability with Multifunctional PV-Inverters in Distributed Energy Systems", to be presented at *10th International Conference on Electrical Power Quality and Utilization* (EPQU), Łódź, Poland.

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