Compensation of Disbalanced Energy Consumption in 3-phase Systems with Asymmetrical Solar Inverter Output

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Abstract- A balancing algorithm was developed to redirect inverter power output between phases to make the energy flow between the utility grid and a three-phase prosumer as symmetrical as possible. Current state-of-the art inverter technology is symmetrical output. Our research proposes a concept with asymmetrical inverter output. The analysis in the current research focuses on the prosumer side and the system boundary is set to the smart meter. Data from a solar station and a three-phase residential consumer was used to prove the concept. It was demonstrated that such algorithm can decrease grid sales and purchases up to 18%. The aim of the study is to develop a possible solution to reduce the electrical energy exchanged with the power grid. The analysis shows, that asymmetrical solar inverter output can cover more consumption directly and reduce the daytime power need from the power grid up to 10%.

Keywords Load balancing, unbalanced consumption, 3-phase system, building energy system, production response.

1. Introduction

Increasing energy demand and necessity for cleaner, greener energy has increased installation of PV panels throughout last years. Many have set up their personal solar station on the roof of their household. These smaller production units (up to 10-12 kW) are established with different purposes. Firstly, to reduce energy consumption from power grid by producing one's own electrical energy. Secondly, to sell excessive energy produced by the power station to the power grid to reduce overall load of the power grid and central energy stations, when possible. Mostly three-phase inverters are used in on-grid systems. When the consumption is distributed evenly between phases – everything works well. Different problems may occur when consumption is disbalanced between the three phases.

Three-phase systems are widely used in the electricity transmission, distribution and even in smaller households and apartment buildings. Throughout national electricity grids all consumers and loads are theoretically distributed nearly equally between phases. In everyday use there is practically always a disbalance in loads between the phases as most of equipment in households is powered by one-phase supply and it is almost impossible to predict when and which apparatus is used and from which phase this load is using energy.

The concept of smart-energy metering includes measurements of energy movements in both directions and all three phases separately. A solar inverter with symmetrical output supplies energy between phases evenly [1]. Situations where one phase is loaded more than another will cause phase-wise asymmetry on the distribution grid. For example, there can be a scenario where one phase's power demand is covered totally with energy from the solar station, the second phase supplies excess energy to the power grid and the third phase needs more energy than the solar station can cover, therefore there needs to be energy imports on this phase from the power grid. This is a situation where energy is moving through the power meter in both directions simultaneously. It is technically efficient to consume as much as possible energy directly on-site [2]. As energy is moving from and to the power grid it means that there is a potential to cover more energy demand directly from the solar station and in the same time use less energy from the power grid. The here presented approach to cover more local consumption from solar energy is to distribute inverter output between the phases intentionally asymmetrically. The management of the individual phases is described in previous research for other purposes like circulating current suppression or, reactive power compensation [1], [3]-[5].

The number of electricity producers has risen in the last years exponentially and the majority of new installations are solar power stations with the purpose of supplying energy for on-site energy consumption and to feed energy to the grid, that cannot be consumed locally [6]. This development has been accelerated and will likely continue in the foreseeable future because of renewable energy policies and energy efficiency requirements like the Nearly Zero Energy Building standard [7]. An electricity consumer that can produce energy on-site for own consumption and for feeding it to the electricity grid is called a prosumer [8]. Renewable energy prosumers connect their generation devices to the electricity grid almost always via inverters. Among other reasons, because of the increased deployment of renewable energy generators inverter topologies and control systems have been developed actively in recent years [9]–[13]. In Europe the majority of these prosumers have three-phase systems. The three-phase inverters currently available have an energy output that is divided between phases symmetrically. In contrast, the three-phase energy consumption of a prosumer is almost never ideally symmetrical [14], [15]. Households and small businesses tend to have higher relative imbalances between phases because single one-phase loads can constitute proportionally a larger share in relation to a small consumer's total electricity consumption [16]. Even redesigning the consumer's electricity system by moving loads from one phase to another would not make the consumption ideally symmetrical at each point of time. The installing of solar power stations on-site to larger consumers like industries or shopping centers has also gained momentum [17].

The state of the art is to increase self-consumption through storage devices or with load shifting [18]–[23]. The here described concept has a similar purpose, but it is achieved without needing storage devices or shifting consumption in time. As a result, the energy production can be directed exactly on the particular phase or phases where it is consumed. When applying the described concept, the energy generation unit itself (in this context, mostly photovoltaic arrays but also smaller scale wind turbines) can remain the same as with conventional inverter system setups. There should be no resulting inconveniences or noticeable changes for the electricity consumer or risks for the consumption devices. To achieve this, the concept needs thorough research and development.

Applying this concept increases the count of different switching operations in solar inverters and DC microgrid and therefore it is essential to protect the system against overcurrent, voltage peaks and different faults that may occur by applying correct protective components to maintain coordination and selectivity of protective equipment.[24].

It is known that solar and wind energy sources have fast changing outputs [25]. In some countries net-metering is used for billing renewable energy prosumers and under this policy the concept would not add economic benefits to the prosumer [26-27].

2. Material and Methods

The state-of-the-art is to distribute solar inverter output symmetrically, so that the total electrical energy is distributed between phases equally, as described in figure 1A. It can cause a situation where energy is exported to the power grid from one phase and imported from the power grid on another phase. The idea of this concept is to compensate energy shortage on one phase not from the power grid, but with asymmetrical solar inverter output, like described on figure 1B. To analyze the efficiency of these kind of inverter alterations two simulations with different electricity production capacities are carried out.

This method may not apply on regions where net metering or other larger timescale-based energy billing principles are used, but areas where energy measurement is based on higher resolution and shorter time-scale or phase-wise energy movement metering is applied, it was concluded that making inverter output asymmetrical reduces bidirectional energy movement and creates economic benefits to the prosumer.

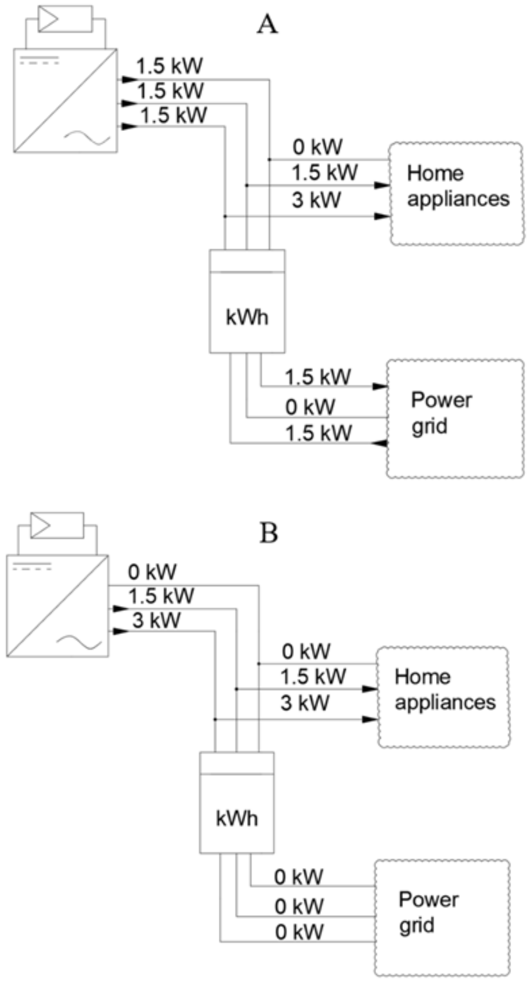

Figure 1. Solar inverter output with disbalanced energy consumption. A – Symmetrical inverter output. B – Asymmetrical inverter output matching consumption

Firstly, to analyze daytime need for electricity, electrical consumption of one household was measured during a period of two weeks in March. All three phases are measured separately with a resolution of 10 min periods. From the overall data, the daytime consumption from 8 AM to 6 PM was extracted and used for further simulations. The total amount of 10-minute time periods where energy movement was analyzed is 888 with a duration of 148 hours. The results of these measurements are presented in table 1 with calculations of phase symmetry/asymmetry. As it shows, the actual loads on different phases are quite asymmetrical and the asymmetry on daytime is even bigger than it is on consumption overall. The biggest load is on phase 2 from where 62% of daytime electricity is consumed and smallest load is on phase 3 from where 11% of daytime electricity is consumed. The difference in consumption between these two phases is six times.

Table 1. Electrical consumption symmetry

	Daytime		Overall	
	Energy, kWh	Symmetry	Energy, kWh	Symmetry
Phase 1	14,915	27%	47,291	30%
Phase 2	34,038	62%	81,42	52%
Phase 3	5,897	11%	27,453	18%
TOTAL	54,85	100%	156,164	100%

The energy production data is measured and summarized similarly for the same period, two weeks of March. Energy from the PV inverter is measured and summarized on 10-minute bases. Total energy production from inverter in two weeks is 74,15 kWh. Solar station installation consists of one one-phase inverter Delta 2.5 and 2,5 kW of installed PV panels. Measured data is used in two different simulations. Firstly, to simulate household with small 2,5 kW production capability on three phases, production data is divided on all three phases (24,72 kWh of electrical energy on each phase). Secondly, to simulate household with larger 7,5 kW production capacity, measured data is used on each phase (74,15 kWh of electrical energy on each phase).

Conventional solar inverter output is symmetrical, but as shown before, energy consumption is not symmetrical on phases. Knowing exact energy need and energy production on each time, the idea is to analyze, is it possible to reduce the amount of energy imported from the power grid by making solar inverter output asymmetrical. Compensating local energy demand on specific phase rather than moving it to the power grid on one phase on importing it from the power grid on another phase at the same time was the main objective of this simulations. The other objective was to achieve symmetrical output towards the power grid (not from inverter, but energy moving to power grid).

The flow-chart describing decision making process on energy distribution between phases and to the power grid is presented in figure 2.

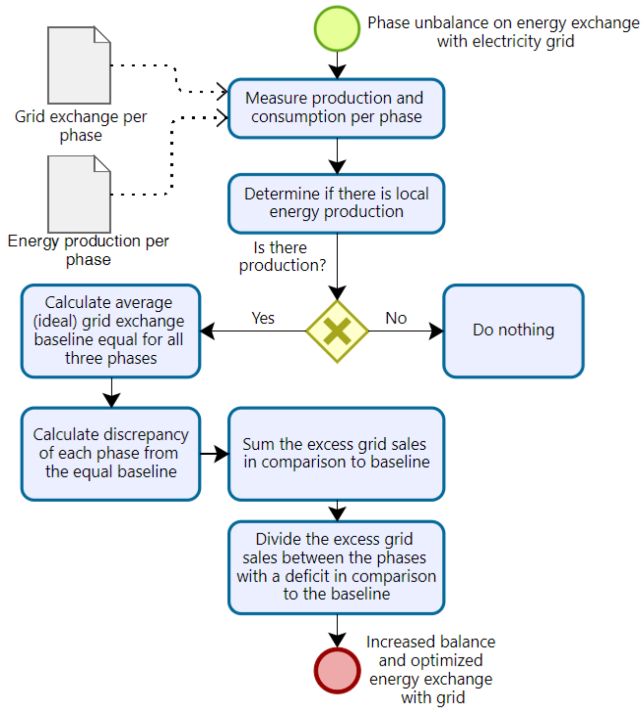

Figure 2. Control logic of the balancing

To achieve highest symmetry in both situations – exporting energy to the power grid and importing energy from the power grid, energy produced (P_{PV}) and energy consumed (P_C) are compared. When $P_{PV} > P_C$, energy to power grid is moving symmetrically and inverter output on different phases (P_{PVi}) is calculated by adding consumption on phase (P_{Ci}) and one-third of excessive energy:

When $P_{PV} < P_C$ and energy from power grid is needed, all consumptions on different phases are ranked from biggest to smallest $P_{C1} > P_{C2} > P_{C3}$ and different scenarios are taken under consideration.

Scenario A. If difference between two largest consumptions (P_{C1} and P_{C2}) is greater than energy produced from solar station (P_{PV}) all energy from solar station is directed to the phase with largest consumption, inverter outputs ranked 2 and 3 respectively are equal to zero

$$P_{c1} - P_{c2} > P_{PV}$$

$$P_{PV1} = P_{PV}$$

$$P_{PV2} = P_{PV3} = 0$$

Energy from solar is reducing purchases on highest ranking phase as described on figure 3A.

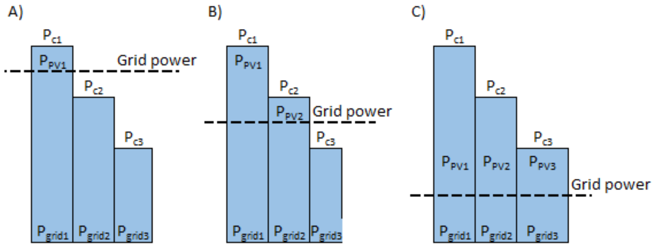

Figure 3. Energy purchase reduction on phases

Scenario B. If the difference between the two largest consumptions (P_{C1} and P_{C2}) is smaller than energy produced from solar station, the energy is divided to cover the phases with the two largest consumptions according to the equations below. Solar inverter output ranked 3 equals zero.

$$P_{c1} - P_{c2} < P_{PV}$$

$$P_{PV1} = P_{c1} - P_{c2} + \frac{P_{PV} - P_{c1} - P_{c2}}{2}$$

$$P_{PV2} = \frac{P_{PV} - P_{c1} - P_{c2}}{2}$$

$$P_{PV3} = 0$$

Energy from solar is reducing purchases on two of the highest ranking phases as described on figure 3B.

Scenario C. When we have enough energy to achieve symmetry in consumptions between phases from the grid, we calculate base need from power grid and divide energy from solar station between all outputs according to the consumptions based on the equations below (and described on figure 3C).

$$P_{c2} - P_{PV2} < P_{c3}$$

$$P_{PV1} = P_{c1} - \frac{P_c - P_{PV}}{3}$$

$$P_{PV2} = P_{c2} - \frac{P_c - P_{PV}}{3}$$

$$P_{PV3} = P_{c3} - \frac{P_c - P_{PV}}{3}$$

3. Results

Household producing electrical energy from solar energy can cover its own demand and direct excessive energy to the power grid. As presented on figure 4, household with larger energy producing capability (7,5 kW) is consuming energy (4A) and capable of selling energy on each phase to the power grid (4B). Applying algorithm to make inverter output asymmetrical can help make overall energy movement towards power grid symmetrical.

Household with smaller electrical energy producing capability (2,5 kW) has different energy movement pattern as presented on figure 4. Households electrical demand is same (5A). Having traditional solar inverter can reduce energy import from power grid on phase 2 and can move energy to the power grid on phases one and three (5B). Applying algorithm on inverter output directs excessive electrical energy to cover power demand on phase two and overall, all three phases are covered with energy from solar and excessive energy is directed to power grid (5C).

Previous figures describe overall energy movement on daytime throughout this two-week time. Even though it looks like producing electrical energy from solar energy can cover all households power demand and make it act like power plant, when to analyze all these 10-minute time periods it shows simultaneous bi-directional energy movement on many periods. Analyzing periods with energy import from power grid and applying algorithm on inverter output shows, how much energy could be used to cover own demand.

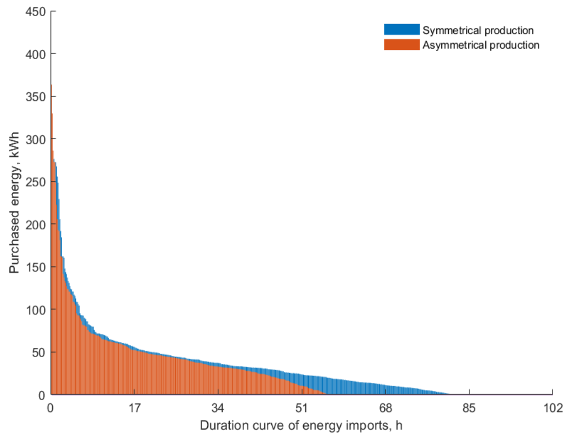

Figure 6A. Reductions on energy purchases from power grid with asymmetrical production. A – 7,5 kW

Figures 6 presents 10-minute time periods with energy import from the power grid. With larger solar inverter (7,5 kW) 478 periods with energy import was detected (6A). Applying algorithm reduced these periods by 30% to the count of 335. Total duration with energy import reduced from 79,6 h to 55,8 h. With smaller solar inverter 627 periods with energy import was detected and applying

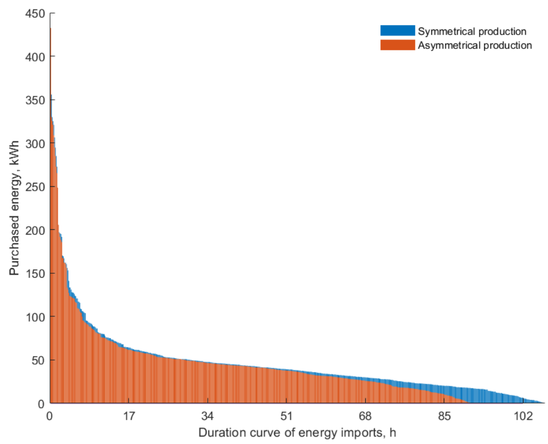

Figure 6B. Reductions on energy purchases from power grid with asymmetrical production. B – 2,5 kW solar

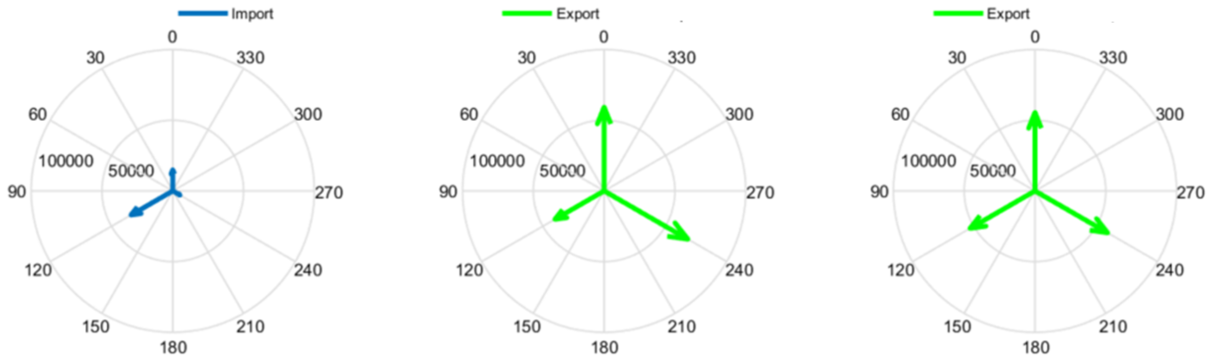

Figure 4. Phase symmetry and energy movement with power grid (larger energy production capability). A – Consumption. B – Consumption with traditional inverter. C – Consumption with asymmetrical inverter output.

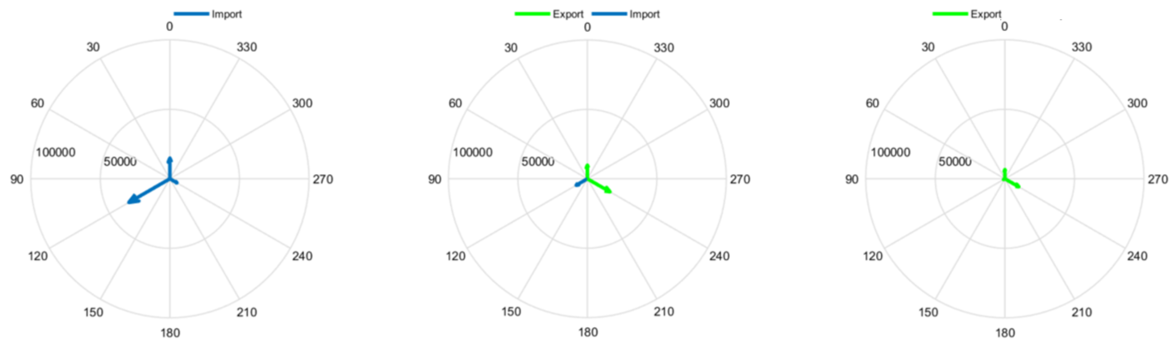

Figure 5. Phase symmetry and energy movement with power grid (smaller energy production capability). A – Consumption. B – Consumption with conventional inverter. C – Consumption with asymmetrical inverter output.

Table 2. Results of simulations

	Energy import without solar energy production						
	10 min periods	**Hours**	**Energy, kWh**		**10 min periods**	**Hours**	**Energy, kWh**
TOTAL Consumption	888	148	54,851		888	148	54,851
	Energy import with solar energy production						
	Simulation 1				**Simulation 2**		
Symmetrical	478	79,6	20,528		627	104,5	29,628
Asymmetrical	335	55,8	16,691		534	89	26,568
Change	-143	-23,8	-3,837		-96	-16	-3,06
Change %	-30%	-30%	-18,69%		-15%	-15%	-10,33%

algorithm reduced this count by 15% to 534. Total duration with energy import reduced from 104,5 h to 89 h.

The cumulative amount of energy imported from the power grid is presented on figures 7. Even with larger solar inverter and its capability to move large amount of electrical energy to power grid (7A), it shows large number of periods when solar energy cannot cover demand on every phase and energy must be imported from power grid. Applying algorithm and smarter energy management the amount of energy imported from power grid was reduced by 18,69%. Applying algorithm on smaller inverter (7B) reduced the amount of energy imported from power grid by 10,33%. Results of two simulations are presented in table 2.

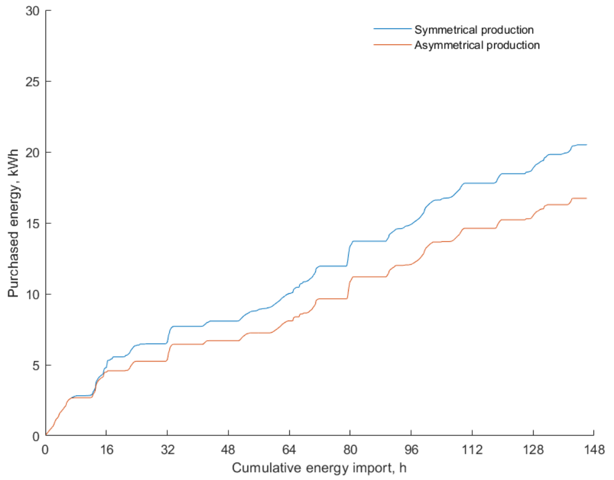

Figure 7A. Cumulative energy from power grid. 7,5 kW solar.

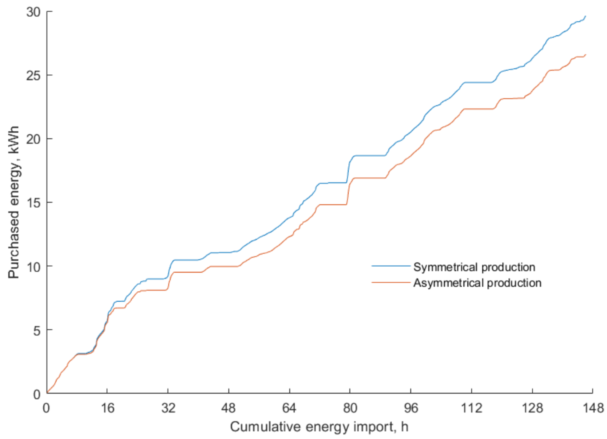

Figure 7B. Cumulative energy from power grid. 2,5 kW solar.

4. Discussion

As simulations showed, electrical energy imported from the power grid could be reduced by 10-19% just by applying a smarter energy management protocol on the inverter output. The amount of energy is not enormous in a single household but adding up many households capable of smarter energy management could give remarkable effect. Smart energy management is one side but there are also many other to take under consideration. Firstly, to be able to manage produced energy in this way and apply algorithm on inverters output, the inverters must be able to do so. Switching loads between phases could cause different power peaks and different harmonic distortions. Every decision making is a process needing time for data gathering, data analysis and harnessing the decision made so all this reaction time of the algorithm and hardware to the changes in energy demand and systems latency is also crucial component of the system. These downsides must be investigated thoroughly and need further considerations.

In addition of smarter energy management and decreasing load on power grid in one energy moving direction, implementing this algorithm can reduce load on power grid in other energy moving direction. Inverter having asymmetrical output in accordance to energy demand on household can distribute excessive energy to power grid as symmetrically as possible. This helps power grid operator to balance loads on different phases more evenly.

Future research can focus on solving the technical implementation issues of the concept.

5. Conclusion

It was concluded on the basis of computer simulations that the balancing of a prosumer system with asymmetrical inverter power is technically possible and sensible. Making solar inverter output asymmetrical is a possibility to increase on-site electricity direct consumption and decrease energy purchases from the power grid. Asymmetrical inverter output has the potential to reduce simultaneous bi-directional energy exchange through smart meters.

Applying the developed algorithm on solar inverter output makes loads on different phases from the power grid side more symmetrical and reduces unevenness on phase loads. The direct consumption of solar electricity was reduced due to the balancing by 18% in a case with 7,5 kW solar panels and by 10% in a case with 2,5kW of solar panels. The duration of bidirectional energy movement was reduced by 30% and 15% respectively.

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