

Improving Efficiency of Power Electronics Converters

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Abstract—This paper presents the analysis of power electronics converters efficiency and the basic procedures and methods for improving its (optimal topology selection, optimized design with selecting switching frequencies and using new types of power switches, application of digital control). Particular attention was paid to possibilities for efficiency improving by parallel connecting multiple converters with the appropriate turn ON/OFF strategy.

Index Terms—Power Electronics Converters, Efficiency Improving, Design Optimization, Digital Control.

I. INTRODUCTION

THE most important characteristics of the power electronics (PE) converters are: low cost, high reliability and efficiency, small size, long life, EMC. Order of importance depends on the specific application. With the contradiction requirements, the design was necessary to achieve certain compromises. Recently, more attention is paid to procedures and methods for improving converter(s) efficiency: selecting the optimal topology, optimized design, and use of modern powerful switch in the power and digital components in the converter control system. Here is given an analysis of losses in the converter with the aim of better understanding the causes of certain types of losses and their impact on the efficiency. A new procedure for efficiency improving, parallel connecting of more converters with the use of appropriate turn ON/OFF strategies is described, which is expected to experience significant applications.

II. IMPORTANCE OF EFFICIENCY IMPROVING

Electric power represents about 40% of the total energy consumption. CPES and EPRI estimates, for 2010, through the PE device will be supplied about 80% of consumers in the US [1]. It is possible to save about 30% of electricity with

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proper use of a new generation of PE devices [2]. Each percentage of improving converter efficiency has positive economic, environmental and other effects. The biggest effects are possible in the control of electric motors, lighting, electronic devices power supply (PFC), and renewable sources. Some specifications have been adopted for the purpose of recognition and popularization of efficient devices. Satisfying these specifications allows assigning certain efficiency qualifications to the devices. For AC input voltage power supplies ≤ 250 W is assigned the ENERGY STAR qualification, if they meet ENERGY STAR specification v2.0 in active and no-load mode and for true power factor [3]. Fig.1. shows given requirements for power supply ≤ 200 W in active mode. For a nominal power ≥ 49 W, average efficiency must be ≥ 0.87 . It is calculated as the arithmetic average value of efficiency, measured for all test voltages at 100, 75, 50, and 25% of the nominal current. In no-load mode (Fig.2.) it is defined AC maximum current. In addition, all qualifying power supplies with ≥ 100 W input power must have a true power factor ≥ 0.9 at nominal current. There are other specifications (e.g. 80PLUS, 85PLUS [4]), for other types of power supplies.

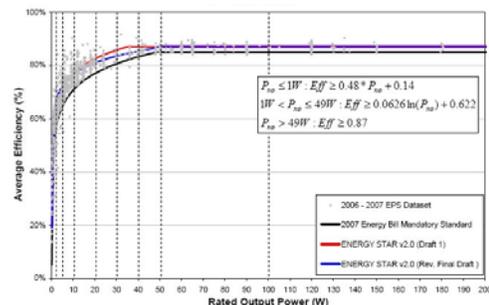


Fig. 1. ENERGY STAR v2.0 revised final draft specification, standard models, to 200 W [3].

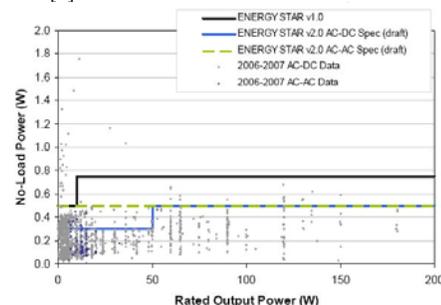


Fig. 2. ENERGY STAR v2.0 revised final draft, no-load spec [3].

III. METHODS FOR EFFICIENCY IMPROVING

Some basic methods and procedures for **PE** converter(s) efficiency improving are:

- Optimal topology selection,
- Design optimization,
- Efficiency optimization by digital control,
- Parallel connection of converters with the proper turn **ON/OFF** strategy.

A. Optimal topology selection

Choosing the right topology is vital to the success of the product and requires detailed knowledge of all the available choices. There are many well known circuits that fit certain applications well, but to find the best solution for a given application is needed to understand how the choice of topology may affect the key parameters, cost, overall size, **EMC** performance and efficiency. The importance each of these parameters varies between application and trade-offs made between each of them have a significant effect on the choice of topology. In order to choose the most appropriate topology designer needs to consider the attributes of possible solutions by adopting a simple scoring process. Each topology have to be evaluated in two stages; firstly for most important, and then for less important characteristics. Each attribute would be ranked, e.g. from “1” meaning bad through to “5” meaning good, and the results of both stages would be weighted together. The scores should be combined with weighting where the most important factors (efficiency, cost) are more heavily weighted than less important. After applying these weightings designer can eliminate unsuitable topologies.

New topologies, which bring significant benefits in terms of the most important characteristics, including efficiency, appear in all areas of application **PE** converters. [5] [6] [7]

B. Design optimization

Converter design optimization is reduced to defining the objective function (efficiency, price and etc., or a combination of them) and finding its maximum/minimum. Defining the objective function means finding a mathematical dependency (efficiency) of all relevant variables in the system [8], while finding the extreme requires development of complex software tools able to quickly solve the task and provide a quantitative analysis of the impact of individual requirements and operating conditions on the value of objective function. The use of optimization techniques in the component design of **PE** systems offers the following attractive advantages: [9]

- Complete automated component design tools can be developed, that allow:
 - improved solutions with respect to traditional design procedures, since more complexity can be considered in the design process,
 - in a reduced design time, once the optimization problem has been specified and the appropriate tools to solve it developed.
- Quick assessment of optimum solutions for different sets of specifications, evaluation of the design objective function sensitivity with the variation of certain specifications and parameters, etc.

-The application of optimization techniques in the design has also an added educational value, since the optimization tool will highlight the critical aspects in each design scenario, allowing the user to focus his attention on these aspects and gain a better understanding of the system design peculiarities.

-In a traditional design approach, each designer often follows his own particular design methodology which, on the other hand, is not rigorously specified anywhere. In contrary, the use of optimization techniques pushes the design team to work jointly to clearly and rigorously specify the design problem and methodology for its solution, which also allows future revisions to improve the design formulation. It provides a written and clear record of the design approach.

On the other hand, there are still several challenges to improving the practicality of optimization techniques:

- Efficient models of the system cost, performance, etc., have to be developed, fast and accurate enough for an optimization process requiring hundreds of design evaluations.
- The component data sheets do not always contain all the required information, and there are often significant differences among the data provided by each manufacturer. Some standardization would help the application of optimization techniques in the design process.
- The formulation of the optimization problem and the development of the tools to solve it require some time. The time required, however, decreases substantially once several design problems have been solved, since the component parameter definition, the component database, certain common models, etc., are already available.
- A real design process is complex, involving several considerations, some of which are hard to identify and express quantitatively. However, once identified they can normally be expressed in some acceptable mathematical form in order to be incorporated into the design problem formulation.

The usage of optimization techniques is particularly recommended in situations when is needed a big improvement in the design of certain characteristics, but also in cases where a small bit of improvement is important. In [9] is given an example of an optimized design of **1 kW PFC** boost converter, with a price as the objective function, where the total price reduced by **58%** compared to the traditional design solution.

On the converter efficiency decisively influence the switching frequency and characteristics of semiconductor switches, which makes them special attention.

1) Optimal switching frequency

Total converter losses are:

$$P_{loss} = P_{cond} + P_{fixed} + P_{sw} \quad (1)$$

- P_{cond} : conducting losses,
- P_{fixed} : fixed losses (independent of the load and f_{sw}),
- P_{sw} : switching losses.

At the critical frequency (f_{crit}), switching losses are equal to other losses. It is switching frequency limit of real converters, because increasing frequency over f_{crit} leads to rapidly decreases of converter efficiency [8]. Another criterion for selecting the switching frequency is related to the satisfied achievement of **EMC**. There is a set of frequencies at which the **EMC** limits are minimum [10], and operation on some of them allows the use of smaller **EMC** filter and greater freedom in the selection of critical components. Optimum switching frequency should be chosen from that set, provided $f_{sw} < f_{crit}$.

2) New powerful semiconductor components

Powerful semiconductor switches have decisive influence on the **PE** converter(s) efficiency. Continuous reduction of switching and conduction losses results in increasing switching frequency simultaneously reducing the converter size, with no reduction in efficiency (or improving efficiency). After decades of development, characteristics of powerful semiconductor switches, based on **Si** technology, moved closer to the limits. Fortunately, in the near future, new technologies and materials will create components with dramatically improved characteristics, which will allow further accelerated development **PE** converters. One of these technologies is based on **SiC** (*Silicon Carbide*), which has some unique characteristics that make it an almost ideal material for high voltage or high temperature operation. First, the thermal conductivity of **SiC** is several times higher than that of **GaAs** and more than three times higher than that of **Si**, which enables the production of components that operate on higher currents. Also, the breakdown voltage of **SiC** is about ten times higher than that of **Si**, so it is possible to make high-voltage Schottky diode which has a negligible reverse current compared to conventional **Si PiN** diode, independent of temperature, operating current and switching di/dt . Their recovery voltage is equal to zero and have almost immediately extinguishing, which drastically reduces the switching losses of **MOSFET** (**IGBT**), and in good part eliminates **EMI**. Converter efficiency is significantly improved, also in many cases with simplifying of **PE** converter topology. **Fig.3.** shows **PFC** boost converter with **Si PiN** diode on the left, and with **SiC** diode on the right side. Converter with **SiC** diode is much simpler and more efficient because there is no need for commutation circuit. [11]

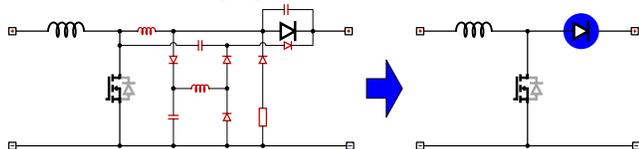


Fig. 3. Boost converter with standard Si PiN and with SiC diode.

Similar effects are achieved by using **SiC** diodes in the inverter, where the average efficiency reached **97.5%** (record **>99%**, **Si 96%**) as a result of reduced losses by **25%**. Applied to the **PV** system, this inverter allows conversion more solar energy into electricity, which, taking into account that the **PV** systems should work at least **30** years, is a great improvement

in energy saving means, faster investment return, and because of lower operating temperature, extended life. First power module with all **SiC** components is introduced in [12]. Basic problems in **SiC** technology are high cost and limited supply.

A revolutionary new power devices, based on **GaN-on-Si** (*Gallium Nitride on Silicon*) technology developed by **International Rectifier Corporation (IR)**, promises to deliver cost-effective performance that is at least ten times better than existing **Si** devices, to enable dramatic reductions in energy consumption and improving of **PE** converter efficiency in end applications in markets such as computing and communications, consumer appliances, lighting and automotive applications. **GaN** transistor with high mobility of electrons (*High Electron Mobility Transistors - HEMT*) provides a major improvement of key characteristics ($R_{DS(on)} \times Q_{sw}$ is **33%** less than the last generation **Si MOSFET**) and allows the converter realization where the product **efficiency** \times **power_density/price** is at order of magnitude better than existing **Si** and **SiC FET**'s [13]. The reverse recovery characteristics (Q_{rr}) of high voltage **GaN** diode is the same as for commercially available **SiC** diodes, both being significantly better than state-of-the-art silicon fast-recovery diodes (**FRED**) (**Fig.4.**). Characteristic is "soft" due to the essential absence of holes in the **GaN HEMT** structure, eliminating the minority carrier effect in reverse recovery charge Q_{rr} . These results are eliminating the otherwise needed filtering (snubber) circuitry. In turn, this reduces system size, cost and weight, and has been used extensively in **PFC** circuitry in **AC-DC** converters using expensive **SiC** diodes and when anti-parallel diode functions are required, such as **IGBT**'s in motor drive circuitry. Demonstration of the advantages of the new **GaN-on-Si** components is shown in [13].

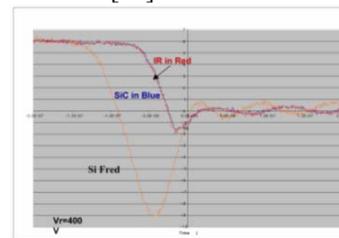


Fig. 4. Reverse recovery characteristics of 600 V GaN, SiC and Si FRED diode [13].

Great progress in reducing size and improving efficiency is achieved by the integration of functional **PE** converter components and using **IPEM** (*Integrated Power Electronics Module*) and **PEBB** (*Power Electronics Building Block* [7]), which, except a powerful switches, contain electronic driver modules, protection, measuring and etc.

C. Efficiency optimization by digital control

The application of digital control brought new opportunities for improving **PE** converters efficiency. Particularly interesting for the application of digital systems is multi-phase control, which is now widely applied to power supply converters for microprocessors, **FPGA** and similar components, as well as the **PFC** circuits. Phase shedding and

other forms of phase control (the order, compensation, balancing) allow converter efficiency optimization over a wide range of operating conditions without degrading other characteristics. The essence of the technique leads to reduce switching losses by turning on as many phases as needed for each load level. Fig.5. shows influence of phase control on the efficiency of four-phase synchronous buck converter ($V_{in}=10$ V, $V_{out}=1$ V, 500 kHz). [14]

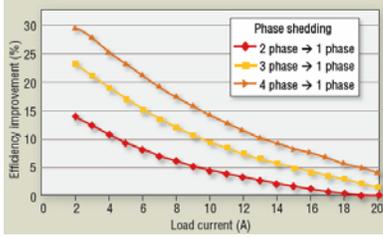


Fig. 5. The influence of phase control on the efficiency of four-phase synchronous buck converter.

Except phase shedding the digital control can remember operating parameters, allowing the controller to make choice how to enable and disable phases in individual situations.

Digital control can further improve the efficiency of the synchronous buck converter by controlling "dead time" of MOSFET. Optimization of MOSFET switching and minimizing "dead time" can improve efficiency by 1% or 2%, depending on the application. [15]

An excellent example of improving efficiency using a digital control is given in [16]. It shows 400 W BCM (Boundary Conduction Mode) two-phase PFC converters, controlled with FAN9612. Part of the FAN9612 synchronization circuit utilizes a maximum frequency clamp to limit frequency-dependent C_{oss} MOSFET switching losses at light load and near zero crossing of the AC input voltage. During the portion of the line voltage for V_{IN} greater than $V_{OUT}/2$, C_{oss} capacitive switching losses are further reduced through a valley-switching technique used to sense the optimal MOSFET turn-on time. Conversely, when V_{IN} is less than $V_{OUT}/2$, the main power MOSFET turns-on using zero voltage switching (ZVS).

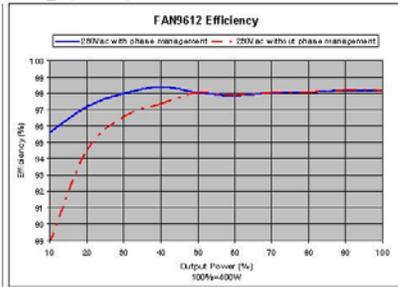


Fig. 6. Phase management efficiency performance [16].

ZVS in conjunction with zero current switching (ZCS), from BCM operation, eliminates MOSFET turn-on switching loss and reverse recovery loss in the output rectifier. FAN9612 automatically disable one phase at 30%, and enable at 40% load current (adjustable in the appropriate input FAN9612). Fig.6. show the measured efficiency improving at low loads 6.5% at $V_{IN} = 230$ V_{AC}.

IV. POWER CONVERTERS EFFICIENCY ANALYSIS

A function $P_{loss}(x)$ represents PE converter losses, where x is related to the output or input current:

$$P_{loss}(x) = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + \dots + a_nx^n, \quad (2)$$

Whose fixed coefficients $a_0, a_1, a_2, \dots, a_n$ correlate well to the different sources of power loss [17] [18]. For instance, a_0 represents fixed overhead losses independent of input/output current. The losses associated with the second coefficient, a_1 are directly related to the input/output current and can be typified as output diode losses, switching losses and losses due to "dead time" in synchronous rectifiers. The third coefficient, a_2 is easily recognized as conduction losses. It is typified as losses in the resistances of the FET, magnetic wiring and interconnect. Useful results can be obtained by considering only the first three coefficients. (2)

$$P_{loss}(i_o) = a_0 + a_{1,o}i_o + a_{2,o}i_o^2 \quad (3.1)$$

$$P_{loss}(i_{in}) = a_0 + a_{1,in}i_{in} + a_{2,in}i_{in}^2 \quad (3.2)$$

The appropriate expressions for the efficiency are:

$$\eta(i_o) = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{v_o i_o}{v_o i_o + a_0 + a_{1,o}i_o + a_{2,o}i_o^2}, \quad (4.1)$$

$$\eta(i_{in}) = \frac{P_{in} - P_{loss}}{P_{in}} = \frac{v_{in} i_{in} - (a_0 + a_{1,in}i_{in} + a_{2,in}i_{in}^2)}{v_{in} i_{in}}. \quad (4.2)$$

Coefficients a_0, a_1, a_2 are determined experimentally by measuring the losses in the three operating points and forming and solving resulting matrices. The solution is simplified if one of the loss measurements is no-load case, where all of the losses are equal to the first coefficient, a_0 . The problem then reduces to two equations and two unknowns, which are easily solved. Once the coefficients are calculated, a loss curve can be constructed showing the three loss types. The presented method for the losses determination in the PE converter give the power supply designer useful insight into understanding the actual circuit losses and good opportunities for the analysis of circuits with different operating modes. Experimental determination of losses should be approached cautiously.

Functions (4.1) (4.2) can be optimized, selecting the parameters a_0, a_1, a_2 , in order to achieve maximum average efficiency: [19]

$$\eta_{max} = \frac{v_o}{v_o + a_{1,o} + 2\sqrt{a_0 a_{2,o}}}, \quad (5.1)$$

and

$$\eta_{max} = \frac{v_{in} - a_{1,in} - 2\sqrt{a_0 a_{2,in}}}{v_{in}} = 1 - \frac{a_{1,in} + 2\sqrt{a_0 a_{2,in}}}{v_{in}}, \quad (5.2)$$

and occur at currents:

$$i_{opt} = \sqrt{\frac{a_0}{a_{2,o}}}, \quad i_{opt} = \sqrt{\frac{a_0}{a_{2,in}}} \quad (6)$$

Equation (6) shows that the coefficient a_1 does not affect the current value at maximum efficiency. This is because it is related to losses that are proportional to output current. So as output current increases, these losses and the output power increases directly, and there is no impact on efficiency. Besides, optimum efficiency occurs at a point where the fixed losses and the conduction losses are equal. This implies that designer should be able to optimize efficiency as long as there is control over the components that determine the value of a_0 and a_2 . Regardless of this, it should be worked to reduce the value of a_1 , in order to improve overall efficiency. The values a_0 and a_2 can be influenced by proper selection of power switch. E.g., selection of power **MOSFET** with a corresponding surface (semiconductor) and active resistance $R_{DS(on)}$, affect control losses, losses of output capacitors and circuit surge protection losses. $R_{DS(on)}$ and the conducting losses are reverse and parasitic capacitance and switching losses connected with them, are directly proportional to the surface. Therefore, it is possible to select the optimal combination of surface and resistance. In [17] is showed that the losses were minimal in the broad area of surface, which allowing the designer flexibility in trading the cost of the **MOSFET** for the loss reduction achieved. Minimum loss occurs when drive loss equals conduction loss. **Fig.7.** is an efficiency plot for three normalized die area around optimum point.

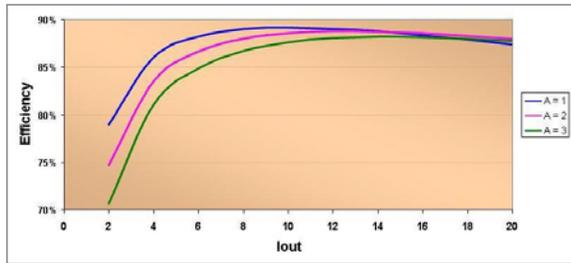


Fig. 7. Efficiency peak occurs before full current rating [18].

At light loads, the efficiency of the larger area is penalized by increased drive losses, while at heavy loads the smaller area device suffers due to increased conduction losses. It is important to note that these curves represent a three-to-one variation in die area and cost. The design with a normalized die area of one is just slightly less efficient than the larger design at full power, and is higher efficiency at light load where the design may typically run.

V. IMPROVING EFFICIENCY BY PARALLEL CONNECTED CONVERTERS

New and very significant opportunities for **PE** converters efficiency improving brings concept based on the parallel connection of multiple converters, with an appropriate turn **ON/OFF** strategy. Let realize the power supply with maximum efficiency, for variable load ($0-P_{nom}$). Identical

converters are available, with maximum power $P_n=P_{nom}/n$ (n -number of the converter), efficiency η_n and possibility for parallel connection and independently turn **ON/OFF**. Two different implementation of the power supply are possible, depending on the **ON/OFF** strategy of individual converters.

S₁: All n converters, with uniform current sharing, are permanently turned **ON** (usually the case). The system acts like single converter which efficiency (η_1) corresponds to the efficiency of an individual converter (η_n):

$$\eta_1 = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{nP_n}{nP_n + nP_{n,loss}} = \frac{P_n}{P_n + P_{n,loss}} = \eta_n \quad (7)$$

- P_{out} : output power of n converters,
- P_{in} : input power of n converters,
- P_n : power of individual converter,
- $P_{n,loss}$: individual converters losses.

The basic disadvantages of this strategy are the low efficiency at light loads, and the fact that all converters are always turned **ON**, which potentially can reduce the reliability and lifetime of power supply system.

S₂: Next ($m \leq n$) converter is turned **ON** only after the ($m-1$) previous turned **ON** converters are loaded with nominal power P_n . The efficiency of power supply system is:

$$\eta_2 = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{(m-1)P_n + P_n}{(m-1)(P_n + P_{n,loss}) + P_n + P_{n,loss}} \geq \eta_n \quad (8)$$

- P_{out} : output power of n converters,
- P_{in} : input power of n converters,
- P_n : nominal power of individual converter,
- P_n : power of individual converter,
- $P_{n,loss}$: converters losses at nominal power,
- $P_{n,loss}$: individual converters losses.

The following figure (**Fig.8.**) show improving of efficiency for 2 and 4 parallel connected converters with **S₂** strategy implemented. For simplicity, examples were made with the assumption that the losses of the converter are constant in the whole range of power, which does not diminish the generality of the solution. In the case of different efficiency curves (maximum efficiency occurs when the power is $<P_n$) essence of strategy remains the same, only the turn **ON/OFF** thresholds of certain converters have to be adjusted. Colored area, on the efficiency diagrams, gives an improvement by using strategy **S₂** compared to **S₁**. The efficiency improving is evidently in the whole range of power. When the all converters are turned **ON** the efficiency is identical to **S₁**. **Fig.8.b** shows that there is a difference in the efficiency improving using 4 compare to the 2 converters. Theoretically, the larger number of converters means higher opportunities to efficiency improving. However, in practice, the numbers of converters that can be simultaneously connected are limited. In addition, a higher number of the converters means reduction of individual power, which after a certain limit leads

to reduced efficiency of individual converter (losses cannot continue to decrease), which negatively affects the overall efficiency.

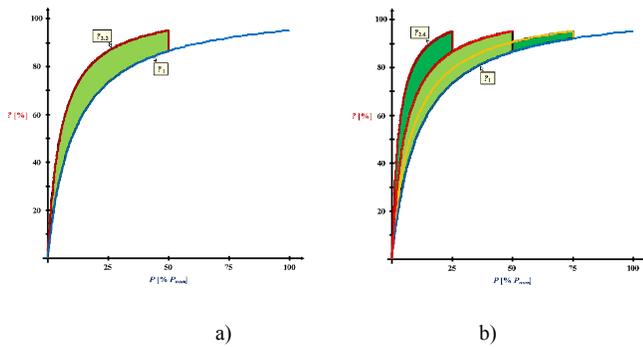


Fig. 8. Efficiency improving by 2 (a) and 4 (b) parallel connected converters.

The big advantage of S_2 strategy is the possibility of individual converters equally using, depending on how long they have each operated, in order to reach higher reliability and sustainability (converters are turned **ON** minimum required time). In addition, if one of the power circuits were to stop working for whatever reason, the others can continue to work independently. It is possible to find practical examples that confirm the benefits of the S_2 . [20] [21]

Great opportunities for the S_2 strategy implementation offer **microinverters**, a relatively new option for optimizing **PV** system efficiency. Microinverters are based on the concept of "**single PV panel-single inverter**". The chief benefit of the microinverter topology is that the system will continue to convert energy even when one (more) inverter malfunctions. Another important advantage is the ability to adjust conversion parameters on each panel. Clouds, shadows and other environmental conditions can vary the output of individual panels. Equipping each panel with its own microinverter allows the system to accommodate its changing load, which provides optimum conversion for both individual panels and the entire system. [22] [23]

Currently, microinverters were connected in the supply system using S_1 strategy. Microinverter with several parallel units would enable the application of S_2 and further improving its efficiency. Besides, in the existing control system for tracking and monitoring is possible, without additional investment, implement S_2 strategy and include as many microinverters is really needed to supply a particular load, with better utilization of individual microinverters/**PV** panels and improving the efficiency of the entire **PV** power supply system.

VI. CONCLUSION

By implementation appropriate design procedures and methods and usage of modern powerful switches in the power and digital components in control part, it is possible to

significantly improve the efficiency of **PE** converters. The completed analysis of converter losses allows a better understanding of their origin and points on possible directions of improving efficiency. The principle of parallel connecting multiple converters, with appropriate turn **ON/OFF** strategy, offers a significant potential to improve efficiency, which is confirmed by the latest developments in applied **PV** power systems.

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