High Efficiency Photovoltaic System with Fuzzy Logic Controller

Branko Blanuša, Željko Ivanović and Branko Dokić

Abstract — **In this paper is presented high efficiency photovoltaic system (PV) with fuzzy logic controller. This system consists of PV panel, boost DC/DC converter and 24V DC load. Control module is realized with fuzzy controller. This controller has double function and it gives references for duty factor and switching frequency of the converter control signal. In this way the PV system works with applied maximum power point tracking (MPPT) method and switching frequency is changed on the way so the converter works with maximum efficiency in continuous current mode. Functionality of proposed model is tested through computer simulations in Matlab and on laboratory prototype.**

Key words: PV system, DC/DC converter, fuzzy controller, MPPT, efficiency optimization.

Original Research Paper
DOI: 10.7251/ELS1721060B

I. Introduction

Electrical energy production from renewable energy sources, increasingly grows and significant, one can say the leading, place have PV panels. This method of power generation from PV systems is one of the cleanest and safest, and there is no acoustic pollution that is characteristic for wind plants.

Although new materials and production techniques of photovoltaic cells were developed, silicon is still in over of 80% the produced photovoltaic cells. The reason is wide accessibility of silicon and the fact that it is not toxic. Monocrystalline and polycrystalline PV cells are two basic types of silicon photovoltaic cells. There is a third type, amorphous silicon, but the efficiency of these cells is lower than in the previous two types and is less used.

One of the basic requirement that is set in front of PV systems is their efficiency. Therefore, there is an intensive research that is carried out into several directions:

- Development of materials for PV panels with a better ratio efficiency/price,
- Optimization of solar system topology from the standpoint of electrical energy production and consumption,
- Maximum utilization of available power of solar panels,
- Maximum efficiency of power converters used in solar systems.

There are significant researches and many methods which are used for a better utilization of available power from PV panels. They are well known as MPPT technique like gradient methods[1], perturbation and observation (P&O) [2], the incremental conductance (IncCond) [3], ripple correlation [4], short circuit current (SCC) and open circuit voltage (OCV) technique [5] etc. Also, there are many techniques based on fuzzy logic [6-7] and the use of artificial intelligence [8-9]. In some papers, a comparison between different MPPT techniques were performed [10-11]. Generally, these techniques vary in complexity, cost, speed of convergence, hardware implementation, and effectiveness.

Application of DC/DC converters in PV systems are wide and significant. These converters are used to connect PV panel to DC consumers. Also, converters can be used as battery chargers, or interfaces between solar panels and DC/AC converters, or electrical grid. One of the significant characteristics of the converters used in solar systems is their efficiency.

Central place in this paper has control module based on fuzzy logic controller. Efficiency optimization algorithm for DC/DC converter and MPPT algorithm are implemented in this module. So, two functions are realized with the one fuzzy controller. Fuzzy based MPPT controller is fast and the output voltage of the PV panel adjusts to meteorological changes, so the maximum power at the panel output is obtained. Also, using the same controller, an adaptive search algorithm for efficiency improvement of the DC/DC converter is implemented. This algorithm is applicable regardless of converter topology.

Simple PV system is discussed in this paper. It consists from PV panel, boost DC/DC converter and 24V DC load. (Fig. 1.). Similar controller with some modifications can be used in more complex PV systems.

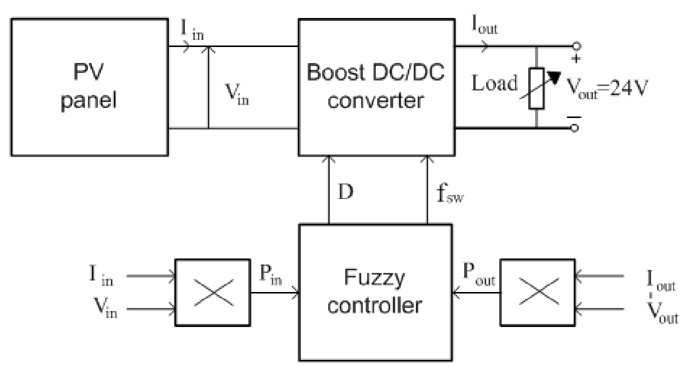

Fig. 1. Block diagram of the PV system.

Manuscript received: May 18th, 2017
Received in revised form: February 2nd, 2018

Branko Blanuša is with the Faculty of Electrical engineering, University of Banja Luka, phone: +387 51 221 824; email: branko.blanusa@etf.unibl.org

Željko Ivanović is with the Faculty of Electrical Engineering, University of Banja Luka, phone: +387 51 221 846; email: zeljko.ivanovic@ etf.unibl.org

Branko Dokić is with the Faculty of Electrical engineering, University of Banja Luka, phone: +387 51 221 820; email: branko.dokic@etf.unibl.org

Organization of paper is as follows:

Loss model of boost DC/DC converter is presented in second section. The realization of control module with the fuzzy controller is given in the third section Proposed controller is tested through computer simulation and laboratory tests. This is presented in the fifth section. Obtained results are summarized in conclusions.

II. Boost Converter Losses

In this PV system boost DC/DC converter is realized in standard topology of this converter [12] (Fig. 2.).

Energy losses in elements of the boost DC/DC converter can be divided into: conduction, dynamic and fixed losses [13]. Total energy loss P_{loss} is expressed as [14]:

$$P_{loss} = P_{cond} + P_{fixed} + W_{TOT} \cdot f_{sw} \quad , \tag{1}$$

where: P_{cond} – conduction losses, P_{fixed} – fixed losses, W_{TOT} – total energy of dynamic loss during one switching period. Product $P_{sw} = W_{TOT} \cdot f_{sw}$ is average value of dynamic power loss, which is directly proportional to switching frequency f_{sw}.

Equivalent scheme of boost converter is presented in Fig. 2. In this case MOSFET is used as basic switch component [15,16] .

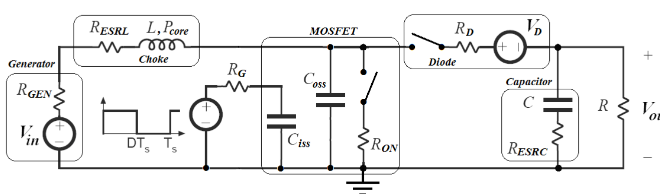

Fig. 2. Equivalent scheme of boost converter with parasitic elements [14].

Conduction losses are directly dependant on loads, and very little dependant on switching frequency. Fixed losses are dependent on neither switching frequency nor load. Semiconductor elements are major source of dynamic losses in the converter. Dynamic losses are very little dependent on power load, but directly depend on switching frequency.

So, It is possible to reduce switching losses by adjusting switching frequency to working conditions. From that reason, the focus in the analysis of power losses is on the dynamic losses.

A Dynamic losses

Dynamic losses in the converter consist of losses in inductor core, transistor and diode. Dynamic MOSFET losses are losses in gate, output capacitance and losses which occur during switch mode change [17,18]. Detailed analysis of dynamic losses in boost DC/DC converter is given in [14].

Total switching losses are equal to the sum of individual switching losses of converter elements and they can be expressed as follows:

$$P_{din} = P_{iss} + P_{Tsw} + P_{oss} + P_{Tdiode} + P_{core} \quad . \tag{2}$$

where P_{iss} is power loss in the MOSFET gate, P_{Tsw} are dynamic losses occur in transition process of switches, P_{oss} is power loss during the process of discharging the output capacitance C_{oss} of MOSFET, when MOSFET is turning on, P_{Tdiode} is transistor dynamic losses, coming from diode recovery time and P_{core} are inductor core losses due to hysteresis and eddy currents

Relations (2) shows that the switching losses in semiconductor elements are function of switching frequency.

Depending on the duty factor, load and switching frequency, the converter can operate in continuous current mode (*CCM*) or discontinuous current mode (*DCM*). In this application it works in CCM. This mode enables independent control of duty factor (*D*) and frequency (f_{sw}) of converter control signals.

III. Control module with fuzzy controller

The control module regulates operation of boost DC/DC converters. It is based on fuzzy controller. This controller controls duty factor and frequency of the converter control signal. In this way two important functions are realized. One is control of PV output voltage, so the MPPT algorithm is realized. Output voltage of the PV panel is changed in the dependency of the temperature and solar radiation intensity, so the maximum output power is achieved This is realized by the duty factor control. The second function of controller is efficiency improvement of the converter, what is achieved by control of switching frequency (Eq.(1) and (2)).

A. Implementation of MPPT algorithm

PV panel is current source, whose output current and voltage, and on that way the power depend from many factors, among which the most important are temperature and intensity of solar radiation.

The dependence of the PV panel output power from its voltage is nonlinear (Fig. 3).

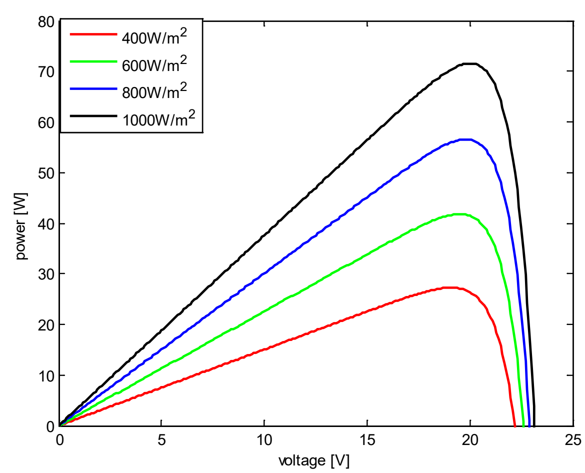

Fig. 3. Output power of PV panel in a funcion of panel voltage for different values of solar radiation

For the realization of MPPT algorithm simple fuzzy controller is used (Fig. 5.). Input in the fuzzy controller is difference of two successive samples of PV panel output power:

$$\Delta P_{in}(n) = P_{in}(n) - P_{in}(n-1)\,, \quad (3)$$

where $P_{in}(n)$ is PV panel output power in moment nT_1, and T_1 is time interval between two successive samples of the panel output power. In this application T_1=0.1s. Output from the fuzzy controller is duty factor (ΔD). By changing of duty factor, output voltage of PV panel is changed, so it works with maximum output power.

Sign of ΔD is determined based on panel output power. If ΔP_{in} increases, sign of ΔD is retained. Otherwise, the sign is opposite.

$$sgn\left(\Delta(\mathrm{D}(n))\right) = \begin{cases} sgn\left(\Delta(\mathrm{D}(n-1))\right) & if\ P_{in}(n) \geq P_{in}(n-1) \\ -sgn\left(\Delta(\mathrm{D}(n-1))\right) & if\ P_{in}(n) < P_{in}(n-1) \end{cases} \quad (4)$$

where $\Delta D(n)$ is change of duty factor in the moment nT_1.

B. Efficiency optimization of boost converter

Algorithm for efficiency optimization of boost DC/DC converter is realized as search algorithm with fuzzy controller (Fig. 4). Boost converter efficiency for given operating conditions (input power and output voltage) can be optimized by adjusting switching frequency what is discussed in Section 2. Changing the switching frequency must not disturbed defined operating conditions of the converter, relating to maximum change of inductor current, maximum ripple of the output voltage and maximum induction in the inductor core.

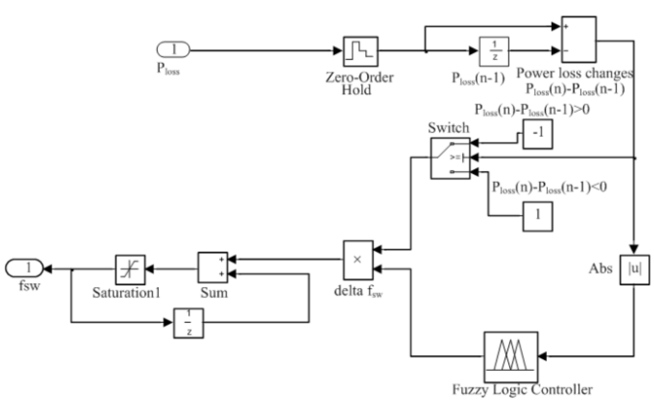

Fig. 4. Search algorithm for efficiency optimization of boost DC/DC converter

This algorithm works as follows. Power loss is calculated as difference between the input and output power of the converter

$$P_{loss}(n) = P_{in}(n) - P_{out}(n) \quad (5)$$

where $P_{loss}(n)$ is converter power loss and $P_{in}(n)$ and $P_{out}(n)$ converter input and output power respectively in the moment nT_2. In this aplication T_2=10ms. The difference of two power loss successive samples is:

$$\Delta P_{loss}(n) = P_{loss}(n) - P_{loss}(n-1). \quad (6)$$

If $\Delta P_{loss}(n)$ is negative, switching frequency f_{sw} keeps its direction. Otherwise, sign of Δf_{sw} is opposite

$$sgn\left(\Delta(f_{sw}(n))\right) = \begin{cases} sgn\left(\Delta(f_{sw}(n-1))\right) & if\ P_{loss}(n) \leq P_{loss}(n-1) \\ -sgn\left(\Delta(f_{sw}(n-1))\right) & if\ P_{loss}(n) > P_{loss}(n-1) \end{cases} \quad (7)$$

Based on $|\Delta P_{loss}(n)|$, value of $|\Delta f_{sw}(n)|$ is determined in the fuzzy controller so the new value of switching frequency in the moment nT_2 is equal to

$$f_{sw}(n) = f_{sw}(n-1) + sgn\left(\Delta f_{sw}(n)\right)\left|\Delta f_{sw}(n)\right|. \quad (8)$$

C. Implementation of fuzzy controller

Fuzzy controller has two inputs and two outputs. One input is output power of PV panels (P_{in}) and second are power losses of DC/DC converter (P_{in}-P_{out}) (Fig. 5). Outputs are duty factor (D) and switching frequency (f_{sw}). Block diagram of the realized control module is shown in Fig. 5.

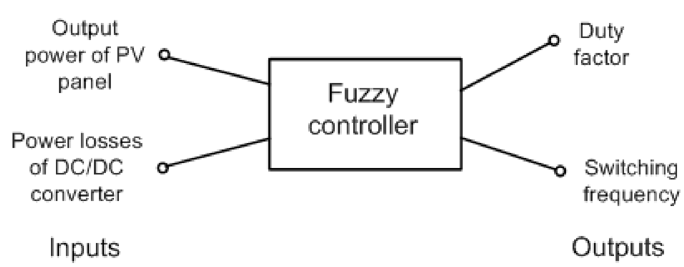

Fig. 5. Block diagram of the realized control module

Fuzzy system has total 12 rules. Set of fuzzy rules is given in Table I.

Table I.
Set of Fuzzy Rules implemented in Application

Number of fuzzy rule	Fuzzy rule
1.	If $\Delta P_{in}(n)$ is big and $sgn(\Delta P_{in}(n))$ is positive then $\Delta D(n)$ is positive big
2.	If $\Delta P_{in}(n)$ is medim and $sgn(\Delta P_{in}(n))$ is positive then $\Delta D(n)$ is positive medium
3.	If $\Delta P_{in}(n)$ is small and $sgn(\Delta P_{in}(n))$ is positive then $\Delta D(n)$ is positive small
4.	If $\Delta P_{in}(n)$ is big and $sgn(\Delta P_{in}(n))$ is negative then $\Delta D(n)$ is negative big
5.	If $\Delta P_{in}(n)$ is medium and $sgn(\Delta P_{in}(n))$ is negative then $\Delta D(n)$ is negative medium
6.	If $\Delta P_{in}(n)$ is small and $sgn(\Delta P_{in}(n))$ is negative then $\Delta D(n)$ is negative small
7.	If $\Delta P_{loss}(n)$ is big and $sgn(\Delta P_{loss}(n))$ is positive then $\Delta f_{SW}(n)$ is negative big
8.	If $\Delta P_{loss}(n)$ is medium and $sgn(\Delta P_{loss}(n))$ is positive then $\Delta f_{SW}(n)$ is negative medium
9.	If $\Delta P_{loss}(n)$ is small and $sgn(\Delta P_{loss}(n))$ is positive then $\Delta f_{SW}(n)$ is negative small
10.	If $\Delta P_{loss}(n)$ is big and $sgn(\Delta P_{loss}(n))$ is negative then $\Delta f_{SW}(n)$ is positive big
11.	If $\Delta P_{loss}(n)$ is medium and $sgn(\Delta P_{loss}(n))$ is negative then $\Delta f_{SW}(n)$ is positive medium
12.	If $\Delta P_{loss}(n)$ is small and $sgn(\Delta P_{loss}(n))$ is negative then $\Delta f_{SW}(n)$ is positive small

Fuzzy type is mamdani. Centroid method of defuzzification is used.

IV. Simulation Results

Simulations of discussed PV system are implemented in MATLAB-Simulink. Experimental verification of the proposed algorithm is tested on the laboratory setup.

There is a linear and step change of the parameters that have the most important impact to the characteristics of the PV panels, temperature (T) and solar radiation intensity (λ) (Fig. 6). Total duration of simulations is 10s. Simulation results which show the performance of the described MPPT algorithm are shown in the figure 7. and 8. Output voltage, output current and the output power of PV panel for the excitation from Fig. 6. are shown in Fig. 7.

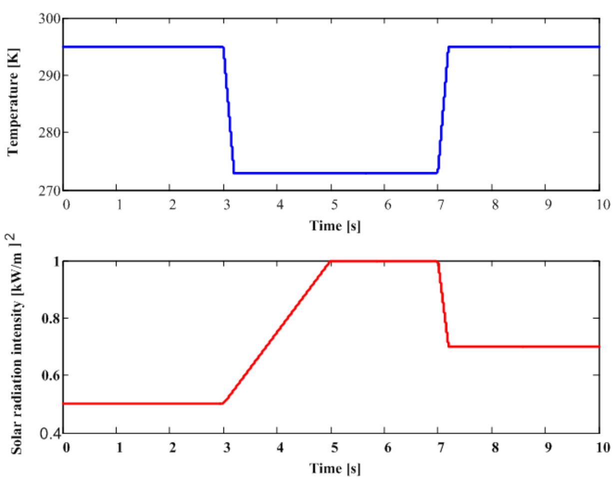

Fig. 6. Graphic of outside temperature and solar radiation intensity used in simulation.

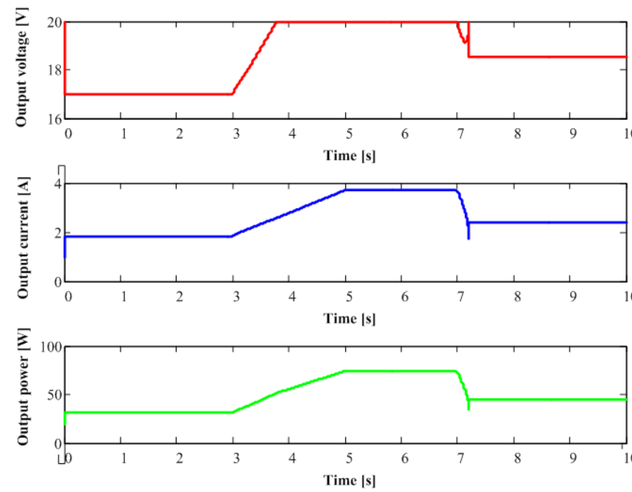

Fig. 7. Graphics of panel output voltage, output current and output power for applied MPPT algorithm based on fuzzy logic and the working conditions shown in Fig. 6.

Graphics of PV panel output power when MPPT algorithm is applied and for constant output voltage V_{po}=0.7V_{oc} (V_{oc} is open circuit voltage for the used PV panel) and specified working conditions (Fig. 6.) are shown in Fig. 8.

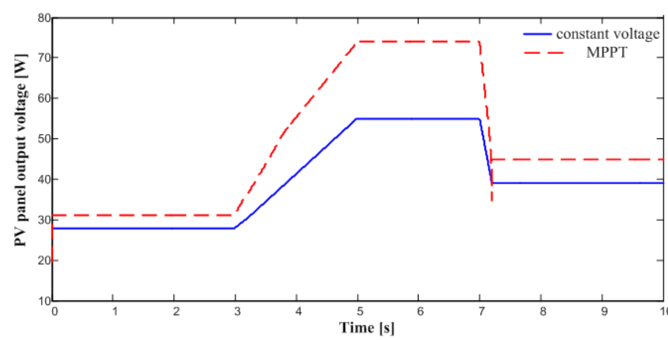

Fig. 8. Graphics of panel output power for constant voltage V_{po}=0.7V_{oc} and applied MPPT algorithm and the working conditions shown in Fig. 6.

Based on Figs. 7 and 8 It can be concluded that the proposed MPPT algorithm is fast and comparable with the fastest MPPT algorithms. Also, for a given working conditions this algorithm obtains maximum o power at the output of PV panel.

Operation of the efficiency controller in the applied boost DC/DC converter in the PV system has been tested through simulations. Obtained results are presented in Figs. 9 and 10.

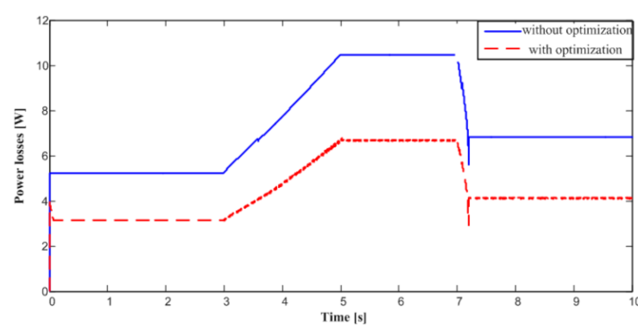

Fig. 9. Power losses for constant switching frequency and with applied efficiency optimization algorithm.

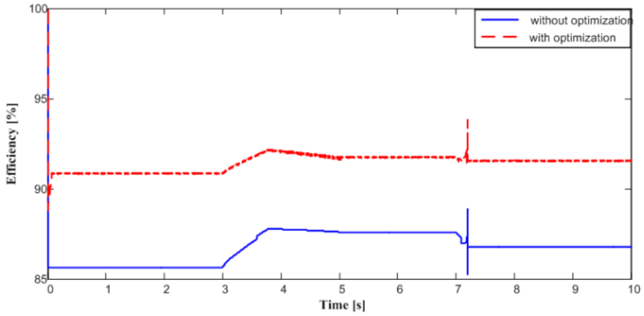

Fig. 10. Boost converter efficiency in observed PV system for constant switching frequency and with applied efficiency optimization algorithm.

Based on the results (Figs. 9 and 10), it can be concluded that the algorithm adjusts the switching frequency to the load. In this way switching losses are reduced and efficiency increased.

V. Experimental Tests

Laboratory setup for experimental tests is shown in Fig. 11. It consists of:

- Autotransformer,
- Rectifier,
- Boost converter,
- MF624 acquisition card, connectors and interface board,
- Electronic load.

This laboratory setup is used to test algorithm for efficiency optimization the efficiency of the DC/DC converter. Autotransformer regulates amplitude of ac voltage on the rectifier input. This voltage is rectified and led to the input of DC/DC converter. Value of this voltage can be changed. Output of DC/DC converter has constant voltage and variable load so the output power is changeable. For input power from 10W to 80W losses and efficiency of the converter are measured when the switching frequency is constant and equal 100kHz. For the same input voltage and output power, losses and efficiency are measured when efficiency optimization algorithm with fuzzy controller is applied. Lower limit of the switching frequency is 20kHz. It is defined by the system constraints related to the maximum current ripple in the inductance and the maximum ripple of the output voltage. Also, the frequency for which the converter has the minimal losses and for given working conditions is measured. For higher input power this frequency is on the lower limit. Only, for less input power frequencies, which gives the minimum switching loss, increase above the lower limit. Results are presented in the Table II and in the Fig. 12. Applied algorithm for efficiency optimization gives a significant efficiency improvement of the converter.

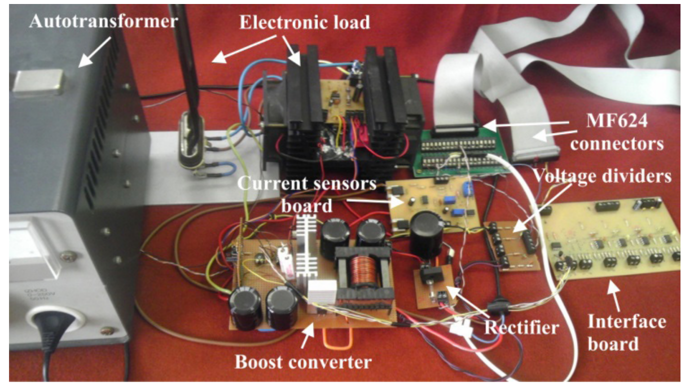

Fig. 11. Laboratory setup for experimental test.

The efficiency of the DC/DC converter in this application is somewhat lower than expected. The reason is that an available converter was used for the experimental test. This converter is not specially designed for this application.

Table II.
Power Losses and Efficiency for Constant Switching Frequency and for applied Algorithm for Efficiency Optimization

P_{in}	80	70	60	50	40	30	20	10
P_{loss} [W] const. f_{sw}	11.6	10.1	8.6	7.15	5.85	4.55	3.25	2.05
η (%) const. f_{sw}	87.3	87.4	87.5	87.5	87.2	86.75	86	83.1
P_{loss} [W] var. f_{sw}	7.3	6.25	5.25	4.33	3.52	2.72	1.95	1.27
η (%) var. f_{sw}	91.6	91.8	91.9	92	91.9	91.6	91	88.7
Optimal f_{sw} [kHz]	20	20	20	20	20	20	20.5	27

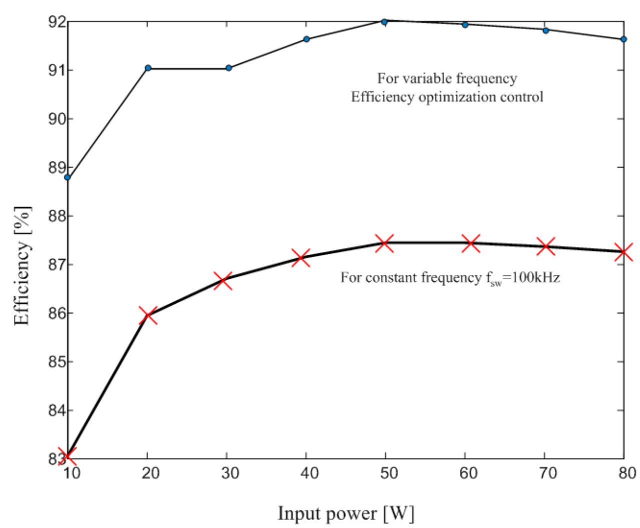

Fig. 12. Converter efficiency for constant switching frequency f=100kHz and for applied efficiency optimization algorithm.

VI. Conclusions

In this paper is presented a system with PV panel, DC/DC boost converter and a variable load.

The control system is realized with fuzzy controller which controls duty factor and a switching frequency of the converter control signal so the MPPT algorithm and efficiency optimization of boost converter are obtained. In this way two significant functions are realized with one fuzzy controller. In both cases, adaptive search techniques have been applied which provide fast convergence to the voltage which gives maximum output power from the panel and the switching frequency for which the power losses in the converter are the lowest. Applied techniques are robust and independent of the parameter changes in the PV panel model, or converter loss model. Results are confirmed through simulations and experimental tests:

1. Maximum utilization of available power from the PV panels. (Fig. 7 and 8)

2. Operation of the DC / DC converter with a switching frequency which provides maximum efficiency for a given working condition. (Figs 9, 10,12 and Table II).

Similar control concept based on fuzzy controller can be used for more complex PV systems.

References

[1] Jianpo Zhang, Tao Wang, Huijuan Ran: A Maximum Power Point Tracking Algorithm Based On Gradient Descent Method, IEEE Power & Energy Society General Meeting, PES '09, Calgary, AB, pp. 1-5, 2009.

[2] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, "Assessment of perturb and observe MPPT algorithm implementation techniques for PV pumping applications," IEEE Transactions on Sustainable Energy, vol. 3, no.1, pp. 21–33, 2012.

[3] H. Kumar and R. K. Tripathi, "Simulation of variable incremental conductance method with direct control method using boost converter," in Proceedings of the Students Conference on Engineering and Systems (SCES '12), pp. 1–5 March 2012.

[4] D. Casadei, G. Grandi, and C. Rossi, "Single-phase single-stage photovoltaic generation system based on a ripple correlation control maximum power point tracking," IEEE Transactions on Energy Conversion, vol. 21, no. 2, pp. 562–568, 2006.

[5] A. Reza Reisi, M. Hassan Moradi, and S. Jamasb, "Classification and comparison of maximum power point tracking techniques for photovoltaic system: a review," Renewable and Sustainable Energy Reviews, vol. 19, pp. 433–443, 2013.

[6] R. Mahalakshmi, Aswin Kumar A. and A. Kumar, "Design of Fuzzy Logic based Maximum Power Point Tracking controller for solar array for cloudy weather conditions," *Power and Energy Systems: Towards Sustainable Energy*, pp. 1-4. 2014.

[7] Y. Soufi, M. Bechouat, S. Kahla and K. Bouallegue, "Maximum power point tracking using fuzzy logic control for photovoltaic system," *2014 International Conference on Renewable Energy Research and Application (ICRERA)*, , pp. 902-906, 2014.

[8] L. M. Elobaid, A. K. Abdelsalam, and E. E. Zakzouk, "Artificial neural network based maximum power point tracking technique for PV systems," *in Proceedings of the 38th Annual Conference on IEEE Industrial Electronics Society (IECON '12),* pp. 937–942, 2012.

[9] Adel Mellit, Soteris A.Kalogirou, MPPT-based artificial intelligence techniques for photovoltaic systems and its implementation into field programmable gate array chips: Review of current status and future perspectives Elsevier, Energy, Volume 70, Pages 1-21, 2014.

[10] Radhia Garraoui; Mouna Ben Hamed; Lassaad Sbita, "Comparison of MPPT algorithms for DC-DC boost converters based PV systems using robust control technique and artificial intelligence algorithm", *12th International Multi-Conference on Systems, Signals & Devices (SSD15)-,* pp 1-6, 2015.

[11] J. Chauhan, P. Chauhan, T. Maniar and A. Joshi, "Comparison of MPPT algorithms for DC-DC converters based photovoltaic systems," *2013 International Conference on Energy Efficient Technologies for Sustainability*, 2013, pp. 476-481., 2013

[12] Frede Blaabjerg, Zhe Chen, and Soeren Baekhoej Kjaer: Power Electronics as Efficient Interface in Dispersed Power Generation Systems, IEEE Transactions on Power Electronics, Vol. 19, No. 5, 2004.

[13] Barry, A., Robert, E., Dagan, M.: DC-DC Converter Design for Battery-Operated Systems, IEEE Power Electronics Specialists Conference, Atlanta, GA, June 18-22, 1995, pp. 103-109, 1995.

[14] Zeljko Ivanovic, Branko Blanusa, Mladen Knezic: Power Loss Model for Efficiency Improvement of Boost Converter, 23rd International Symposium on Information, Communication and Automation Technologies, pp. 1–6, 2011.

[15] Jon, K.: *Synchronous buck MOSFET loss calculation with Excel Model*, Fairchild Semiconductor Publication, 2006.

[16] Wilson, E.: *MOSFET Current Source Gate Drivers, Switching Loss Modeling and Frequency Dithering Control for MHz Switching Frequency DC-DC Converters*, PhD thesis, Queen's University Kingston, Ontario, Canada, February, 2008.

[17] Robert, E., and Dragan, M.: Fundamentals of Power Electronics, (Kluwer Academic Publishers, 912 pages, 2nd edn. 2001).

[18] Van den Bossche, A., Valchev, V. C.: Modeling Ferrite Core Losses in Power Electronics, International Reveiw of Electrical Engineering, pp. 14-22., 2006.

[19] K Benlarbi, A Mokrani, M.S. Nait-Said, A Fuzzy Global Efficiency Optimization of Photovoltaic Water Pumping System, Elesevier, Solar Energy, Volume 77, Issue 2, pp. 203-216, 2004.

[20] Ahmad Al Nabulsi, Ammar El Nosh, Abdulrahman Ahli, Mohamed Sulaiman, Rached Dhaouadi, Efficiency Optimization of 150W PV system dual axis tracking and MPPT, IEEE International Energy Conference, pp. 400-405, 2010.