Model of High Efficiency Solar System with DC/DC converter

Branko Blanuša, Željko Ivanović and Branko Dokić

Abstract - Model of high efficiency solar system with photovoltaic (PV) panel, DC/DC converter and 24V DC load is presented in this paper. Control modul is realized with fuzzy controller. This controller controls duty factor and switching frequency of the converter. In this way the solar system works with applied maximum power point tracking (MPPT) algorithm and switching frequency which provides converter work with maximum efficiency. Functionality of proposed model is confirmed through computer simulations in Matlab.

Keywords - Model, Solar system, fuzzy controller, MPPT, efficiency optimization.

I. Introduction

Electrical energy production from renewable energy sources, increasingly grows and significant, one can say the leading, place have solar panels. This method of power generation from solar 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 photovoltaic (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. Most photovoltaic cells are monocrystalline type. The efficiency of these solar cells is 15-20%. Efficiency of polycrystalline cells is lower and around 12-15%. Production process of photovoltaic cells of amorphous silicon is simpler than the previous two. However, the drawback is the poor efficiency, which ranges from 6-8% [1].

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

- Development of materials for solar 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.

Branko Blanuša, Željko Ivanović and Branko Dokić are with the Department of Electronics, Faculty of Electronic Engineering, University of Banja Luka, Patre 5, 78000 Banja Luka, Bosnia and Herzegovina, E-mail: {branko.blanusa, zeljko.ivanovic, branko.dokic}@etfbl.net.

Application of DC/DC converters in solar systems are wide and significant. Over these converters solar panels are connected to DC consumers. Also these converters can be used as battery chargers, or interfaces between solar panels and DC/AC converters. The proposed algorithm is applied to a simple solar system consisting of solar panel, boost DC/DC converter and 24V DC consumers (Fig1.), although it can be used in more complex solar systems and for different types of DC/ DC converters.

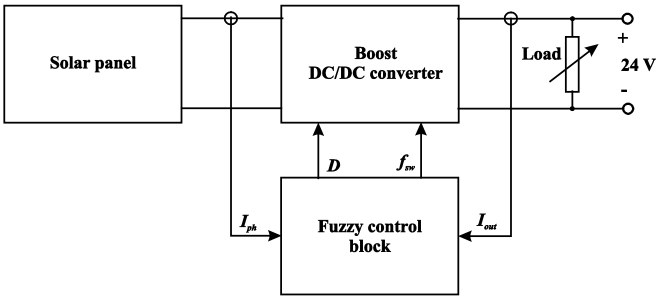

Fig. 1. Block diagram of the realized solar system

Central place in this paper has control module with fuzzy controller. It controls the DC/DC converter so the MPPT algorithm is applied. Also, for a given operating conditions swiching frequency is adjusted, so the converter operates with maximum efficiency.

Organization of paper is as follows: Loss model of boost DC/DC converter, and its dependence from the switching frequency is described in the second chapter. The realization of the fuzzy controller for implementation of MPPT algorithm and converter efficiency optimization in a solar system is presented in the fourth chapter. Work of the proposed controller is tested through computer simulation. The results are presented in the fifth chapter. Obtain results are summarized in conclusions.

II. Boost Converter Losses

Boost DC/DC converter is realized in this solar system where standard topology of this converter is often used [2] (Fig1.).

Energy losses in elements of the boost converter can be divided into: conduction, dynamic and fixed losses. Total energy loss P_{loss} is expressed as [3]:

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

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}. Conduction losses are directly dependant on loads, and very little dependant on switching frequency. Fixed losses are dependent on neither switching frequency nor load. They are consisted of controller power supply current, and leakage currents of transistor, diode and capacitors. These losses are often much less in comparison to conduction and dynamic losses, so these can be neglected.

Semiconductor elements are major source of dynamic losses in the converter. During switching transitions, very high power losses can occur in semiconductor devices. Although the switching time of semiconductor elements is very short, average power loss can be substantial. Dynamic losses are very little dependent on power load, but directly depend on switching frequency.

Equivalent scheme of boost converter is presented on Fig. 2. MOSFET is used as basic switch component. It is assumed that the converter elements are linear, and time, frequency and temperature independent.

Turned on MOSFET is modeled with R_{ON}, while diode is modeled with serial connection of voltage source V_D and resistance R_D. Input MOSFET capacitance C_{iss} and output capacitance C_{oss} are also included in the model. The input generator is modeled with serial connection of internal resistance R_{GEN} and the ideal voltage generator. Equivalent losses in converter supply circuit are presented with R_{GEN} resistance. In this case supply circuit is photovoltaic module.

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.

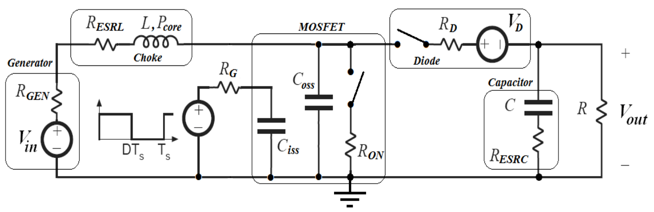

Fig. 2. Equivalent scheme of boost converter with parasitic elements [4]

A. Conduction losses

In order to determine the average power of conduction loss it is necessary to determine the effective current value through the parasitic resistance and the average current value through the voltage sources in boost converter model.

The average power of conduction losses in converter, when it operates in continuous mode, is equal to sum of average power in all elements, i.e.:

$$P'_{cond} = R_{GEN} \cdot I'^2_{Leff} + R_{ESRL} \cdot I'^2_{Leff} + R_{ON} \cdot I'^2_{TReff} + \\ + R_D \cdot I'^2_{Deff} + V_D \cdot I'_{Davg} + R_{ESRC} \cdot I'^2_{Ceff} \quad (2)$$

B. Dynamic losses

Dynamic losses in the converter consist of losses in choke core, transistor and diode. Dynamic MOSFET losses are losses in gate, output capacitance and losses which occur during switch mode change.

Power loss in the MOSFET gate is given follows as [5]:

$$P_{iss} = C_{iss} \cdot V_{cg}^2 \cdot f_{sw} \quad (3)$$

where C_{iss} is equivalent input capacitance of MOSFET, V_{cg} is supply voltage of gate control circuit and f_{sw} is switching frequency.

Power P_{oss} is power loss during the process of discharging the output capacitance C_{oss} of MOSFET, when MOSFET is turning on:

$$P_{oss} = \frac{1}{2} C_{oss} \cdot V_{Tr}^2 \cdot f_{sw} \quad (4)$$

where voltage V_{Tr} is equal to output converter voltage (Fig. 1).

Dynamic losses occur in transition process of switches. The average value of these losses can be shown as:

$$P_{Tsw} = k \cdot (t_{vr} \cdot I_{L\max} + t_{vf} \cdot I_{L\min}) \cdot V_{out} \cdot f_{sw} \quad (5)$$

where t_{vr} and t_{vf} are voltage rising and falling time respectively. Constant k is in the range between 1/6 and 1/2 [6].

Transistor dynamic losses, coming from diode recovery time, exist only when the converter operates in continuous mode and can be described as [7]:

$$P_{Tdiode} = V_{out} \cdot (I_{L\min} \cdot t_{rr} + Q_r) \cdot f_{sw} \quad (6)$$

where: V_{out} – output voltage of boost converter, t_{rr} – diode recovery time, Q_r – accumulated charge in pn junction area. These losses occur during switching of the transistor, when diode continues to conduct in opposite direction until the Q_r is discharged.

Choke core losses are due to hysteresis and eddy currents. To calculate the losses in the core, with sufficient accuracy, following relation can be used [8]:

$$P_{core} = k \cdot f_{sw}^{\alpha} \cdot \Delta B^{\beta} \cdot V_{core} \quad (7)$$

where V_{core} is volume of choke core, k, α, β are coefficients that can be found in technical specifications of core manufacturers, while ΔB is maximum induction in the core.

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

$$P_{din} = P_{iss} + P_{Tsw} + P_{oss} + P_{Tdiode} + P_{core} \qquad (8)$$

Relations (8) shows that the switching losses in semiconductor elements are function of switching frequency.

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 converter control signals, pulse-width modulated (PWM) signals. In this way two important functions are realized. One is control of converter input voltage, so the MPPT algorithm is realized. This is achieved by duty factor control. The second is maximum efficiency of the converter, what is achieved by control of switching frequency (Eq. 8). So, fuzzy controller has two inputs and two outputs. One input is output power of solar panels and second is power losses of DC/DC converter. Outputs are duty factor of converter control signals and second is switching frequency. Block diagram of the realized control module is shown in Fig. 3.

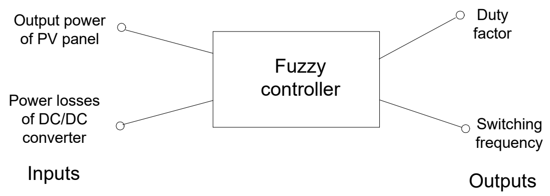

Fig. 3. Block diagram of the realized control module

A. Implementation of MPPT algorithm

Solar panels are current sources, 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 solar panel output power from its voltage is nonlinear. This dependence, for different values of temperature and solar radiation intensity, is shown in Figures 4. and 5. Taking into account the low efficiency of solar panels, it is very important control the panel output voltage so the maximum output power is achieved.

For the realization of MPPT algorithm simple fuzzy controller is used (Figure 3). One input in the fuzzy controller is difference of two successive samples of solar panel output power

$$\Delta p_{po}(n) = p_{po}(n) - p_{po}(n-1), \qquad (9)$$

where $p_{po}(n)$ is solar panel output power in moment nT_I, and T_I is time interval between two successive samples of the panel output power. Output from the fuzzy controller is change of solar panel output voltage ΔV_{po}.

Sign of ΔV_{po} is determined based on panel output voltage. If ΔV_{po} increases, sign of ΔV_{po} is retained. Otherwise, the sign is opposite

$$\operatorname{sgn}\left(\Delta\left(V_{pn}(n)\right)\right) = \begin{cases} \operatorname{sgn}\left(\Delta\left(V_{po}(n-1)\right)\right) \text{ if } p_{po}(n) \geq p_{po}(n-1) \\ -\operatorname{sgn}\left(\Delta\left(V_{po}(n-1)\right)\right) \text{ if } p_{po}(n) < p_{po}(n-1) \end{cases} \qquad (10)$$

where $\Delta V_{po}(n)$ is change of panel output voltage in the moment nT_I.

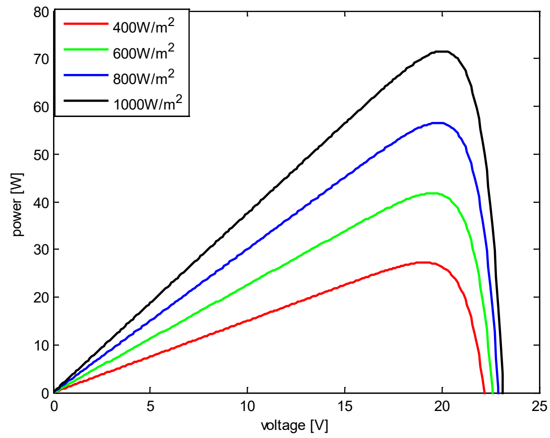

Fig. 4. Output power of solar panel in a funcion of panel voltage for different values of solar radiation

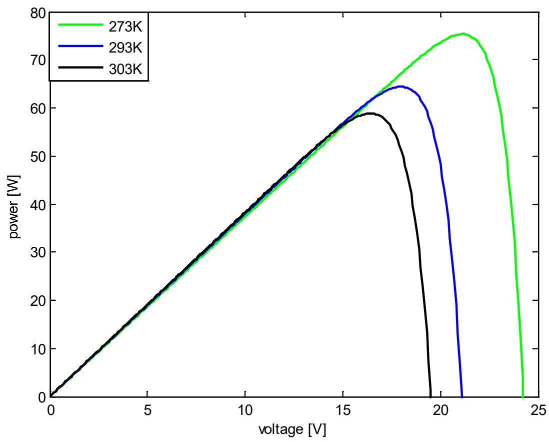

Fig. 5. Output power of solar panel in a funcion of panel voltage for different ambient temperatures

From the obtained values for the panel output voltage (input voltage of the boost DC/DC converter), new value of duty factor is determined

$$D(n) = 1 - \frac{v_{po}(n)}{V_{co}}, \qquad (11)$$

where $D(n)$ is duty factor of boost DC/DC converter control signals in the moment $nT1$ and V_{co} is converter output voltage.

B. Efficiency optimization of boost converter

Algorithm for efficiency optimization of boost DC/DC converter is realized as search algorithm with fuzzy controller. 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 be disturbed defined operating conditions of the converter relating to maximum change of choke current, maximum ripple of the output voltage and maximum induction in the choke core.

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

$$P_{cL}(n) = P_{ci}(n) - P_{co}(n), \tag{12}$$

where $P_{cL}(n)$ is converter power loss and $P_{ci}(n)$ and $P_{co}(n)$ converter input and output power respectively in the moment nT_I. The difference of two power loss successive samples is calculated as

$$\Delta P_{cL}(n) = P_{cL}(n) - P_{cL}(n-1), \tag{13}$$

If $\Delta P_{cL}(n)$ is negative, change of switching frequency (Δf_{sw}) has same direction. Otherwise, sign of Δf_{sw} is opposite

$$\operatorname{sgn}\left(\Delta\left(f_{sw}(n)\right)\right) = \begin{cases} \operatorname{sgn}\left(\Delta\left(f_{sw}(n-1)\right)\right) \text{ if } P_{cL}(n) \le P_{cL}(n-1) \\ -\operatorname{sgn}\left(\Delta\left(f_{sw}(n-1)\right)\right) \text{ if } P_{cL}(n) > P_{cL}(n-1) \end{cases} \tag{14}$$

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

$$f_{sw}(n) = f_{sw}(n-1) + \operatorname{sgn}\left(\Delta f_{sw}(n)\right)\left|\Delta f_{sw}(n)\right|. \tag{15}$$

In this way the switching frequency is changed so the the inverter works with minimum power losses for a given working conditions.

IV. Simulation Results

Simulations of described solar system are implemented in MATLAB. Simulation results which show the performance of the described MPPT algorithm are shown in the Fig. 7. and 8. It is assumed that 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 (χ) (Fig. 6). Fig. 7. shows the output voltage, output current and output power for applied MPPT algorithm, and characteristics of temperature and solar radiation intensity shown in Fig. 6.

Graphics of PV panel output power for applied MPPT algorithm and for constant output voltage V_{po}=0.7V_{oc} with specified operating conditions (Fig. 6.) are shown in Fig. 8.

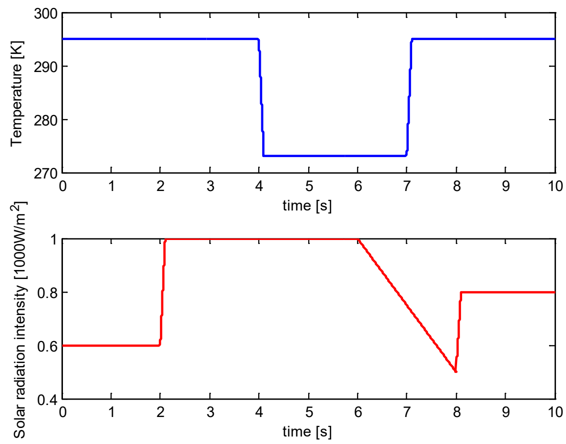

Fig. 6. Graphic of outside temperature and solar radiation intensity used in simulation

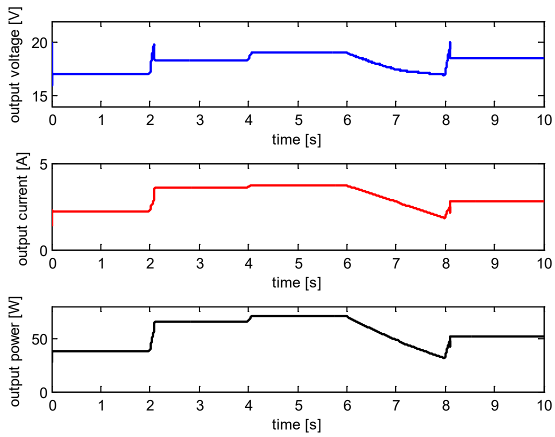

Fig. 7. Graphics of panel output voltage, output current and output power for applied MPPT algorithm based on fuzzy logic and the working conditions shown in Fig. 6.

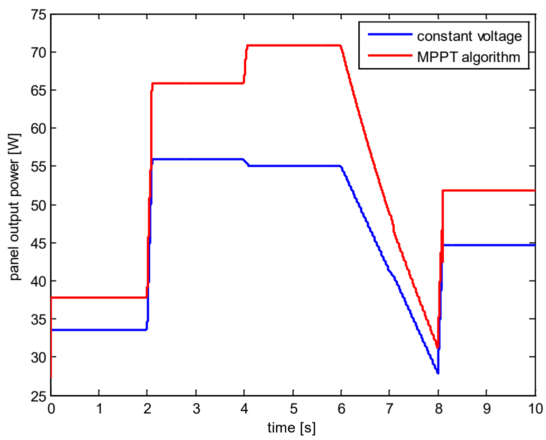

Fig. 8. Graphics of panel output power for constant voltage and applied MPPT algorithm and working conditions shown in Fig. 6.

Based on Fig. 7. and 8. it can be concluded that the proposed MPPT algorithm is fast and provides obtaining maximum power from the PV panel for given working conditions.

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

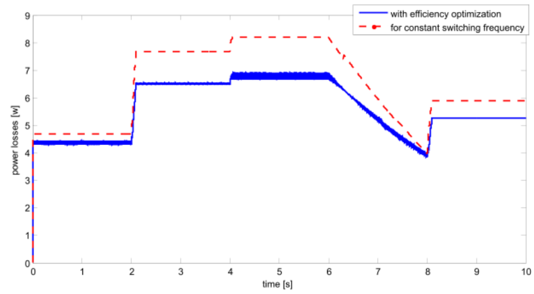

Fig. 9. Power losses for constant switching frequency and with applied efficiency optimization algorithm

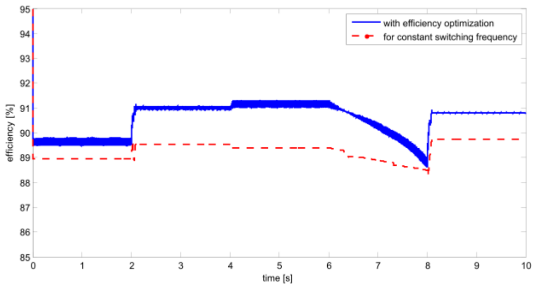

Fig. 10. Boost converter efficiency in observed solar system for for constant switching frequency and with applied efficiency optimization algorithm

Based on the results (Fig. 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. These results correspond to the theoretical analysis in Section 2.

V. Conclusion

In this paper is presented a system which consists of photovoltaic panels, a DC/DC boost converter and a variable resistive load.

The control circuit is realized with fuzzy controller which controls duty factor and a switching frequency of the converter.

The following results have been achieved:

- Maximum utilization of available power from the PV panels (Figs. 7 and 8)

- Operation of the DC / DC converter with a switching frequency which provides maximum efficiency for a given working conditions (Figs. 9 and 10).

The system is modeled and tested in the MATLAB/Simulink.

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