Green power supply for an intelligent traffic light enhanced with visible light communications capabilities

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***Abstract*—This paper presents the development of an enhanced power supply designed for an intelligent traffic light used as a visible light communications emitter. In the context of an increasing preoccupation for alternative energy sources, the system is being supplied with solar energy which is converted in electric energy by a photovoltaic panel. In order to improve the efficiency of the panel, the system is enhanced with a patented solar tracking system and a microcontroller which is continuously monitoring the provided energy and is deciding its optimal use. The extra energy supplied by the solar panel can be stored in a supercapacitors block and used during unfavorable weather conditions or during the night time.**

***Keywords*— green power system; intelligent traffic infrastrucutres; solar tracker; supercapacitors; visible light communications**

I. Introduction

The greenhouse emissions reached alarming levels [1] and immediate actions must be taken in order to prevent irreversible changes in global or regional climate. Although growth is slowing down, the global energy consumption is expected to increase with 30% by 2040 [2] and consequently, a major shift toward clean energy sources is needed to address the problem. This interest is materializing in a fast deployment and in falling costs for ecofriendly energy technologies [2], [3]. Thus, in just 7 years, from 2010 to 2017, the cost of the photovoltaic panels has dropped by 70% [2]. In addition to the usage of clean energy technologies, the society also seeks new ways to reduce energy consumption while maintaining or even improving the comfort. Currently, lighting counts for 10% to 20% of the total electricity consumed [3]-[5], being an area where major energy saving is possible. In this domain, LED lighting sources emerge as energy efficient and highly reliable while having extended lifetime. Thus, it is expected that in the near future, LEDs will totally replace the classical light sources [6] - [8]. This measure has the premises of bringing major energy savings.

This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS/CCCDI - UEFISCDI, project number PN-III-P2-2.1-PED-2016-2011, contract 36 PED/2017, within PNCDI III. The infrastructure used in this work was supported from the project "Integrated Center for research, development and innovation in Advanced Materials, Nanotechnologies, and Distributed Systems for fabrication and control", Contract No. 671/09.04.2015, Sectoral Operational Program for Increase of the Economic Competitiveness co-funded from the European Regional Development Fund.

In addition to improving energy efficiency of lighting sources, LEDs are also capable of fast switching, being suitable for communication purposes. As a result, a novel wireless communication technology has emerged based on Visible Light Communications (VLC) which provides an energy efficient solution suitable for indoor communications as well as for outdoor short-to-medium distance applications, such as inter-vehicle communications or communication-based traffic safety applications [9] - [13]. Thus, the VLC technology uses for data communications the light generated for illumination or signaling purposes and does not need any extra power to generate the carrier wave. For automotive applications, VLC has a great potential but it also faces plenty of challenges [12]. The ability to adapt to a highly unpredictable environment is currently one of the key challenges, as it has the premises to provide significant developing support for the other challenges, as well [12], [13].

In the upper-mentioned context, our research efforts were focused on developing a traffic light with visible light communication capabilities and environment adaptive functions. The proposed traffic light is intended to be energy efficient as well as energy independent being enhanced with a green energy power supply. An invention patent on this topic has been submitted by our research group to the National Office for Inventions and Trademarks [14]. This paper addresses the issues related to the design, development and implementation of an enhanced eco-friendly power supply for the intelligent VLC traffic light. The traffic light requires an electrical current of approximatively 600 mA and a 9V voltage. Its energy independence during daytime is ensured by a 40W photovoltaic panel enhanced by a sun tracking mechanism. The unused energy produced during the day is stored in a supercapacitor, as a backup power supply for the nighttime. The energy provided by the photovoltaic panel is managed efficiently by a low power microcontroller which monitors the provided power, analyzes the priorities and decides on its optimal usage.

978-1-5386-1495-2/18/$31.00 ©2018 IEEE

II. DISCUSSIONS ON THE SOLAR TRACKING SYSTEM

According to existing research, the energy performances of a photovoltaic panel can be improved by up to 60% with the help of a solar tracking system [15] - [17]. Thus, instead of having a fixed panel facing south, a mechanical system is continuously changing the panel orientation achieving Maximum Power Point Tracking (MPPT). Nevertheless, the selection of the driving system involves a compromise between performances and cost. In general, as the accuracy of the sun tracking improves, the tracking system equipment becomes more complex and thus, more expensive.

The solution proposed for our intelligent traffic light power supply (Fig.1) consists of a polycrystalline photovoltaic panel which is continuously rotated toward the sun by means of a flexible intermediate structure motor and electromechanical actuators with paraffin [14]. To clarify the system's efficiency, the performances of the paraffin thermal actuators are presented in Fig. 2. The response of the paraffin electromechanical actuator is a PT_1T_m transient process. The evolution of the step unit response and the speed of the actuator's transient regime are dependent on the amount and on the composition of the working environment used to activate the actuator, on the working environment temperature and on the actuator operating position.

The thermal energy required for the actuation of the thermal actuators can be transmitted by convection (natural or forced), by thermal conduction or even by radiation. The mechanical energy required to rotate the panel is produced based on the paraffin's ability to change its volume (about 15-20%) as it is changing from the solid phase to the liquid phase. Compression and expansion in the actuator body produces significant hydrostatic pressure which is transformed by the actuator into mechanical torque as a linear motion of the piston.

Figure 3 illustrates the operation of the solar motor with flexible intermediate actuating structure [18], which actuates the sun tracking system. The photovoltaic panel's supporting shaft represents the rigid rotor of the motor and it is placed in a circular support. Several thermo-mechanical actuators with paraffin having diametrically opposed positions are mounted on this support. Each actuator can be thermally excited by the sun or by a Peltier element battery associated with a cooler consisting of a mechanical radiator and a fan to activate the cooling. Thus, through a set of drive rods along with a flexible and an immobile intermediate structure, the actuators act on the rotor. The frictional tangential forces generated by the contact between the rotor and the flexible intermediate structure move the rotor, respectively, the panel in the direction of the arrow.

Figure 4 shows the deformations evolution of the flexible intermediate structure [19], [20] with the rigid rotor being exposed to the action of the forces generated by the pairs of actuators activated successively. The paraffin actuators are grouped two by two, in diametrically opposed positions. Thus, through a movable rod they act simultaneously on the flexible intermediate structure which takes the form of an ellipse disposed on the surface of the rotor. The radial forces deforming the rotor are transformed into tangential forces that make the rotor to rotate in the opposite direction. The excitation of the actuator pairs grouped in diametrically opposed positions is made by direct exposure to the sun or by the photovoltaic source via a pulse distributor.

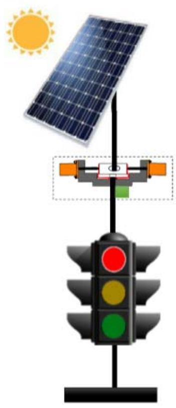

Fig. 1. Design of the traffic light with sun tracking system

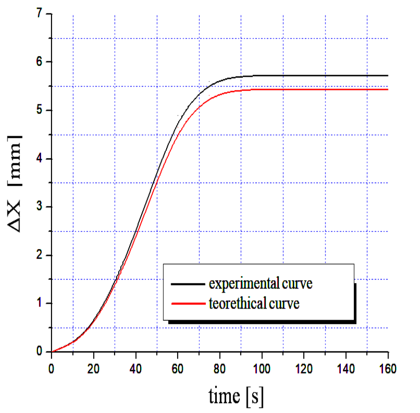

Fig. 2. Performances the thermal actuators with paraffin

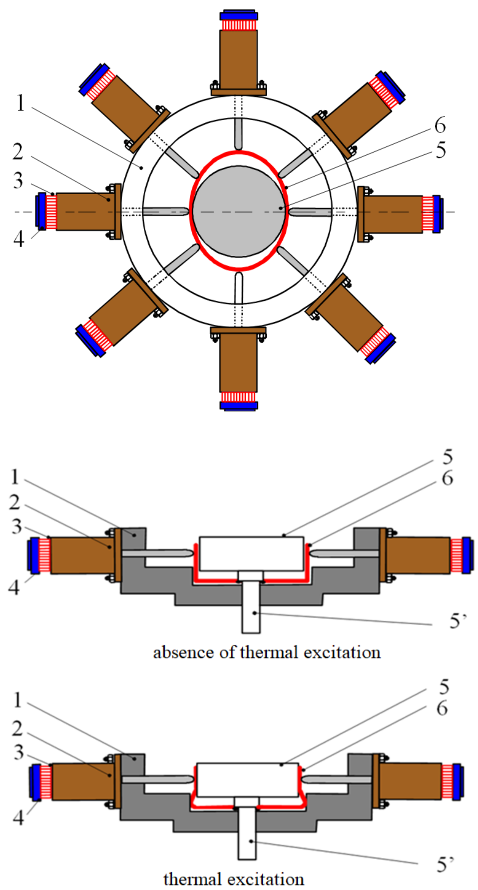

Fig. 3. Description of the solar motor with flexible intermediate actuating structure: 1 - circular support; 2 - proper thermo mechanical actuator; 3 - Peltier element battery; 4 fan; 5 - rigid rotor; 5 '- shaft; 6 - flexible intermediate structure

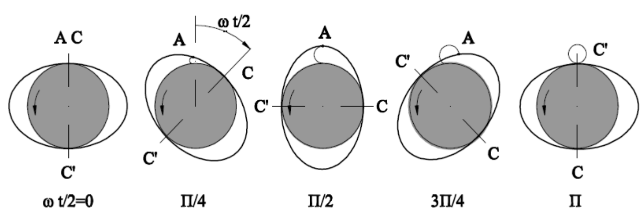

Fig. 4. Description of the flexible intermediate drive structure deformation under the action of the forces generated by the pairs of paraffin thermomechanical actuators

An alternative to the usage of paraffin-based actuators for panel orientation is represented by a DC servomotor powered by the solar panel. This tracking system is adequate for extreme weather conditions due to the lower energy consumption. At nighttime and in unfavorable weather conditions, the traffic light is being supplied by the unused energy captured during the daytime and stored in the supercapacitors source.

III. DISCUSIONS ON THE POWER MANAGEMENT SYSTEM

A. *System's architecture*

Figure 5 illustrates the schematic of the proposed power supply, which consists of two DC-DC step-down converters, a linear power supply, a low power microcontroller (i.e. MSP 430G2553), a supercapacitors unit and a DC-DC step-up converter. The central component of the source is the microcontroller responsible for managing the entire energy flow. The microcontroller is powered by the photovoltaic panel through a linear source. Furthermore, as its functioning is vital for the entire system, it also uses a 1F capacitor as a backup energy source. Due to its low power consumption (i.e. below 140 µA), the energy stored in this capacitor can power the microcontroller for several hours.

The schematic of the first DC-DC step-down converter is illustrated in Fig. 6. The purpose of this block is to convert the 16V voltage provided by the photovoltaic panel into an 8.1V voltage at up to 1A necessary which will be further used to power the traffic light, via the step-up converter. According to the algorithm described in Section III.C, this converter is *on* only when the current provided by the panel is high enough to power the traffic light.

The second DC-DC converter is also used in a step-down configuration and it is responsible for charging the supercapacitors unit. Its schematic is illustrated in Fig. 7. Although it is connected to the photovoltaic solar panel, the converter only works when it receives an *on* command from the microcontroller on the DN_C pin, according to the implemented algorithm. In order to prevent the supercapacitors overcharging, the microcontroller continuously monitors their voltage. Thus, when the voltage of a 3 capacitors series is 8V or when the voltage of an individual capacitor is above 2.66V, the microcontroller disables the charging of the supercapacitors to prevent their destruction. In order to avoid a negative impact on the functionality of the traffic light by extracting too much energy, this block also monitors the voltage provided by the panel. Thus, if the voltage drops below 16V, AO1 interrupts the supply to the block until the voltage rises again to the optimal value.

The third DC-DC converter (Fig. 8) is used in a step-up configuration (commanded by the UP signal) and provides the source output power of 9V and up to 1A. The step-up converter provides a constant 9V voltage at its output while having an input voltage between 2.5 - 8.1V. Its input energy might be provided either by the photovoltaic panel through the DN converter (in daytime) or by the supercapacitors block. The step-up converter is powered through two Schottky diodes, and it is designed based on the AP1609 integrated circuit.

Besides powering the traffic light, the extra energy of the photovoltaic panel is stored in a unit consisting of three 2.7V supercapacitors (i.e. 3W at 3000F each) connected in series. Depending on the required autonomy, additional supercapacitors could be connected in parallel. More details regarding this unit are provided in the next section.

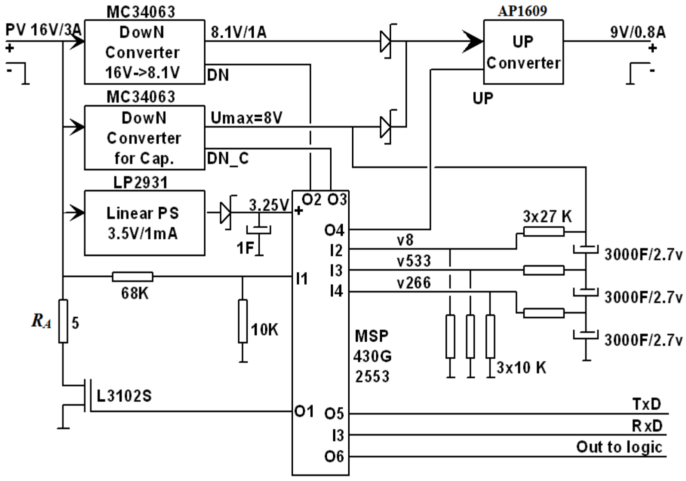

Fig. 5. Representation of the proposed power supply

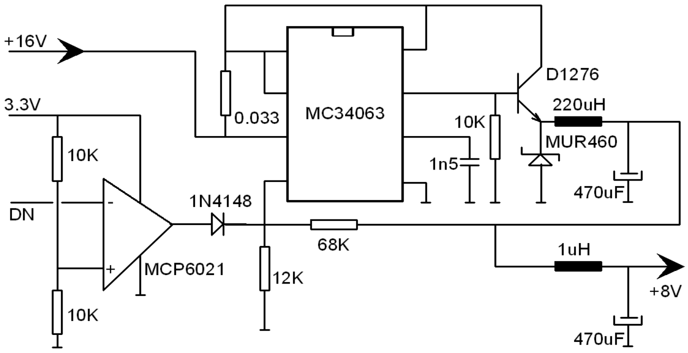

Fig. 6. Schematic of the 16 to 8.1 V DC-DC step-down converter (DN)

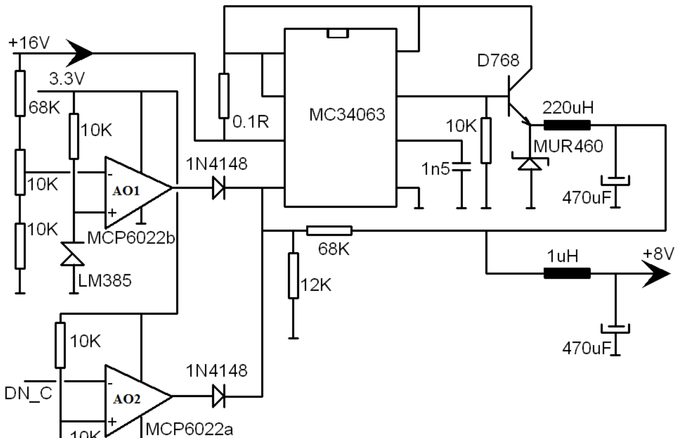

Fig. 7. Schematic of the DC-DC down converter (DN_C)

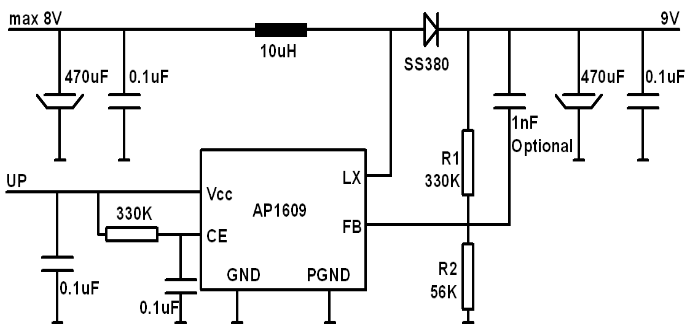

Fig. 8. Schematic of the DC-DC step-up converter

B. The benefits of the supercapacitors unit

Classical accumulators (i.e. alkaline or acid) are commonly in use for energy storage. Nevertheless, despite several advantages, their major disadvantage is given by the limited number of loading cycles (i.e. 300 - 2000). From this point of view, supercapacitors have more than 500.000 duty cycles and, unlike the accumulators, they are not affected by complete discharge. They can also work in an extended temperature range without being affected. Thus, supercapacitors can commonly work at temperatures between -40^0 and +65^{0}C, whereas existing patents describe electrolytes that can properly work at temperatures lower than -80^{0}C [21]. On the downside, one of the capacitor disadvantages is the large voltage variation at its terminals, which is incompatible with most electronic equipment. For this reason, the energy of the supercapacitors is processed by an additional block (i.e. the step-up converter) which provides the equipment (i.e. traffic light in this case) with a constant voltage. In addition, supercapacitors also have a lower specific energy, compensated by a higher specific power. Another important disadvantage of supercapacitors is related to the cost. Currently, this cost is 3 to 5 times higher compared to the traditional accumulators with similar energy performance. Nevertheless, this higher deployment cost is recovered from the improved reliability and the extended lifetime, making them very suitable when extended and extensive usage is projected. Moreover, as the performances of supercapacitors will be fully confirmed, the costs could drop significantly due to mass adoption. An example of a high power system operating with supercapacitors is presented in [22]. In this case, there are several supercapacitors in series and a two-stage load regulator. The first stage controls only the MPPT of the solar panels, whereas the second stage controls the charge of the supercapacitors block at constant power.

C. The energy management plan

Figure 9 illustrates the flow of the energy management plan. This flow is assumed to begin with the supercapacitors unit completely discharged and low ambient light (i.e. early in the morning). In this case, the only source in use is the one supplying energy for the low power microcontroller which is supplied at 3.5 V and up to 140 µA. At this point, the microcontroller periodically checks the voltage supplied by the photovoltaic panel. When this voltage is above 16V, the microcontroller begins to determine the value of the generated current. These operations are accomplished by applying a 1 ms impulse on the MOSFET transistor's gate, by reading the voltage drop on R_A and by determining the current. When the provided current is above 100 mA, the microcontroller switches on the second DC-DC converter (i.e. DN_C=1), which begins charging the supercapacitors block. This second DC-DC converter is able to extract the maximum current while maintain the voltage in the 15 - 16 V region, as this region is associated to the maximum power point of the photovoltaic panel. The maximum voltage supplied by this source should be below 8 V, in order not to exceed the working voltage of the supercapacitors.

While charging the supercapacitors block, the microcontroller monitors the current provided by the photovoltaic panel, and when its value is about 1A, it stops the supercapacitors charging and enables the 8.1 V supply and the step-up converter powering the traffic light. From this point, the traffic light is *on*, and while the supercapacitors voltage is above 3V, short photovoltaic panel voltage breakdowns do not affect the traffic light's functionality. At this time, the microcontroller continues monitoring the electrical current, and when this value is above 1.2A, it enables the 8V source which continues to charge the supercapacitors block. Thus, at this point the traffic light is directly powered by the photovoltaic panel through the DN step-down converter, while the supercapacitors block is maintained full for backup. The energy management is monitored and controlled by the microcontroller enabling the power supply to achieve the optimal use of the energy provided by the photovoltaic panel.

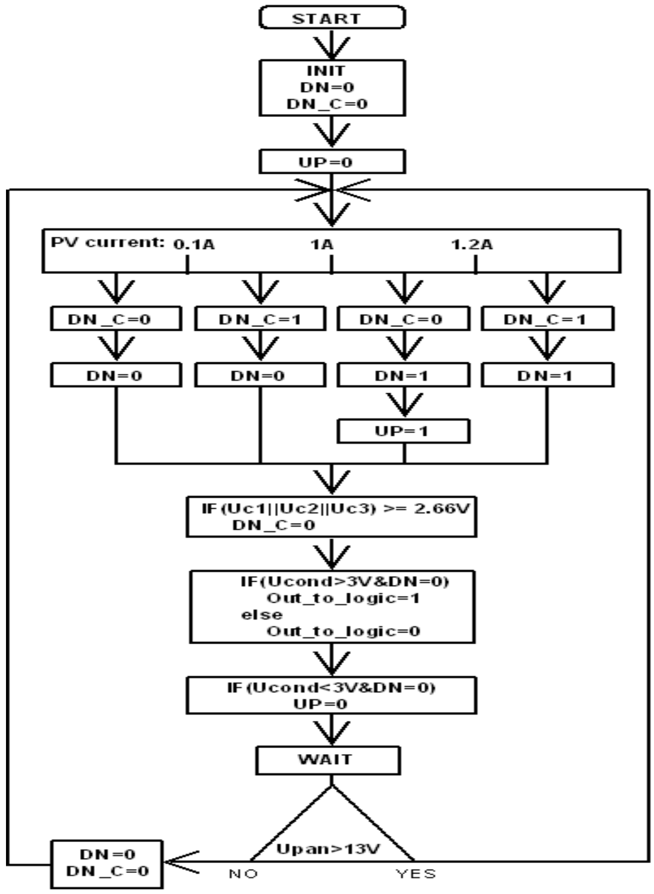

Fig. 9. Energy management flowchart

D. The power supply energy efficiency

This section presents the experimental evaluation of the power supply efficiency. The first experiment was aimed to test the scenario when there is no sunlight and the traffic light is powered from the supercapacitors unit. Figure 10 illustrates the efficiency of the step-up converter as a function of the supercapacitors unit voltage for different output currents. For low output currents (i.e. 93 mA) the supercapacitors unit can be in use until its voltage drops as low as 2.5V. A 1000F capacitor (i.e. the equivalent of the three 3000F supercapacitors series) charged at 8V can provide an energy of 32000J (approx. 9Wh). As the step-up converter can work only while the voltage is above 2.5V, a discharged supercapacitors unit will still hold 3125J, which is less than 10% of its total energy. Nevertheless, as the required output current increases, this limit increases as well. Thus, for an output current of 625 mA, the supercapacitors unit can be in use only while the voltage is above 5.5V. In this case, 46% of the energy remains in the unit. Thus, a feasible solution is to reduce the output current as the voltage of the supercapacitors unit is decreasing. For the case of the traffic light, such a measure is fully justified because it is assumed that the voltage drops as there is no sun to power the photovoltaic panel. In such a case, even if the power provided to the traffic light is decreasing, the contrast to the dark remains high and the visibility of the traffic light is not affected. Moreover, for each class of traffic lights there are certain limits of luminous intensity [23]. Thus, in daytime the traffic light can work at the upper limit, whereas in nighttime, its luminosity can be at the lower limit, maintaining a constant visibility.

The second experiment aimed to determine the efficiency of each converter (see Fig. 5) as a function of its output current. As showed in Fig. 11, the efficiency for the 0.1 - 1A current range is between 65 and 80% for the two step-down converters and between 70 and 83% for the step-up converter, indicating that further improvements could be applicable. Nevertheless, according to the management plan, the two down converters are in use during daytime to supply the traffic light (DN) or to charge the supercapacitors unit (DN_C). In this case, the traffic light functionality is not affected by the efficiency, as the sun can compensate this energy loss. During the nighttime, when the traffic light is working on supercapacitors, the performances of the step-up converter become very important determining the traffic light working time. Thus, in this case, the efficiency of the step-up converter is between 70 and 83%. As the maximum efficiency is obtained for an output current of 400 mA, the current could be set in this region to extend the traffic light autonomy.

Although the efficiency of converter blocks could be further enhanced, the experimental tests have already confirmed the effectiveness of the proposed design. Existing IC converters claim to provide efficiency above 90%. However, it their case, this efficiency is achieved only for ideal conditions and for specific input voltages. Nevertheless, as the input voltage modifies, the efficiency of the circuit is affected. In our case, the converters should work in an extended input voltage range between 2.5 – 8V. Moreover, according to existing research the sun tracking system can improve the panel system's efficiency by up to 60%. Additionally, this energy is efficiently managed by the microcontroller, further enhancing the efficiency, and thus, the energy loss due to converters is compensated.

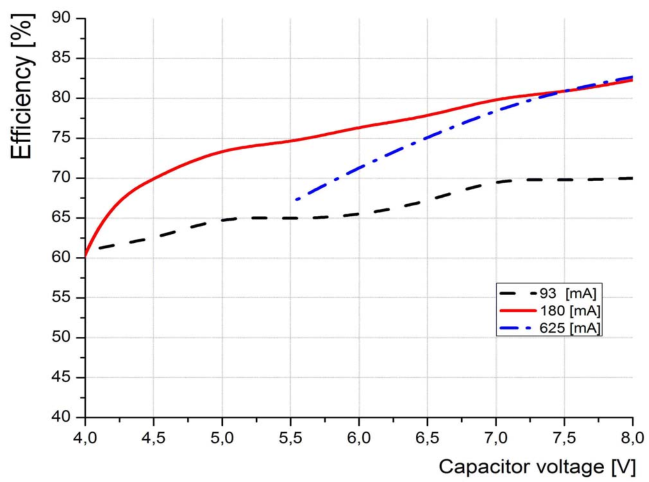

Fig. 10. Efficiency of the step-up converter as a function of the supercapacitors voltage for different output currents

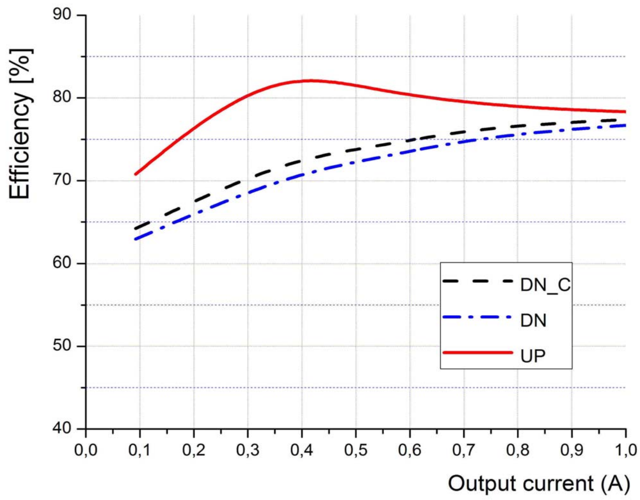

Fig. 11. Efficiency of the converters as a function of the output current

This work also confirmed the benefits associated to the usage of supercapacitors for energy storage applications. In their case, a 1000F unit consisting of the three 2.7V and 3000F supercapacitors series charged at 8V can power the traffic light between 1 and 4 hours (depending on the output current). Thus, to obtain full autonomy, 3000 to 12000F supercapacitors batteries could be used. A summary of the traffic light's working parameters as a function of the input current is provided in Table I.

TABLE I. TRAFFIC LIGHT WORKING PARAMETERS AS A FUNCTION OF THE INPUT CURRENT

Input current at 8.4V [mA]	***180***	***400***	***625***
Traffic light illuminance at 50 cm [lux]	240	350	500
Traffic light autonomy for a single 8.1V and 1000F supercapacitors unit [min.]	245	115	55

IV. CONCLUSIONS

This paper presented the development of a green energy power supply designed to provide energy independency to an intelligent traffic light used as a visible light communications emitter. Thus, instead of relying only on the power grid, the traffic light uses photovoltaic panels as an alternative energy source. In order to improve the efficiency of the photovoltaic panels, the design is enhanced with a solar tracking system able to provide up to 60% extra power. During nighttime, the traffic light is powered by the energy stored in supercapacitors as they offer significantly extended lifetime and improved flexibility. The system is also enhanced with a microcontroller and an intelligent energy management algorithm which monitors the parameters of the energy charging process optimizing the energy usage and preventing malfunctions. Furthermore, as the energy of the supercapacitors unit is decreasing, the microcontroller can reduce the source's output current, in order to extend the traffic light working time.

REFERENCES

[1] V. Ramanathan, and G. Carmichael, "Global and regional climate changes due to black carbon" *Nature Geoscience* **1**, 221–227, 2008, doi:10.1038/ngeo156

[2] Int. Energy Agency, World Energy Outlook 2017, 14 Nov. 2017.

[3] U.S. Energy Information Administration, "Annual Energy Outlook 2017 with projections to 2050," Released January 5, 2017.

[4] Yoshi Ohno, "Impact of LED lighting on Worldwide Energy Saving and Role of Optical Metrology" *APEC Regional Workshop on Measurement Challenges in Renewable Energy and Climate Science*, Oct. 29, 2015.

[5] U.S. Energy Information Administration, "Comercial Bulidings Energy Consumption Surveys - Trends in Lighting in Commercial Buildings", Released: May 17, 2017.

[6] M. Cole, H. Clayton and K. Martin, "Solid-State Lighting: The New Normal in Lighting," in *IEEE Trans. Ind. Appl.*, vol. 51, no. 1, pp. 109-119, Jan.-Feb. 2015, doi: 10.1109/TIA.2014.2328790

[7] M. Schratz, C. Gupta, T. J. Struhs and K. Gray, "A New Way to See the Light: Improving Light Quality with Cost-Effective LED Technology," in *IEEE Industry Applications Magazine*, vol. 22, no. 4, pp. 55-62, July-Aug. 2016. doi: 10.1109/MIAS.2015.2459089

[8] X. Long, J. He, J. Zhou, L. Fang, X. Zhou, F. Ren, T. Xu, "A review on light-emitting diode based automotive headlamps", in *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 29-41, 2015.

[9] A. M. Căilean, B. Cagneau, L. Chassagne, M. Dimian and V. Popa, "Novel Receiver Sensor for Visible Light Communications in Automotive Applications," in *IEEE Sensors Journal*, vol. 15, no. 8, pp. 4632-4639, Aug. 2015. doi: 10.1109/JSEN.2015.2425473

[10] A. M. Căilean, M. Dimian, V. Popa, L. Chassagne and B. Cagneau, "Novel DSP Receiver Architecture for Multi-Channel Visible Light Communications in Automotive Applications," in *IEEE Sensors Journal*, vol. 16, no. 10, pp. 3597-3602, May15, 2016. doi: 10.1109/JSEN.2016.2529654

[11] A. M. Cailean and M. Dimian, "Impact of IEEE 802.15.7 Standard on Visible Light Communications Usage in Automotive Applications," in *IEEE Communications Magazine*, vol. 55, no. 4, pp. 169-175, April 2017. doi: 10.1109/MCOM.2017.1600206

[12] A. M. Căilean and M. Dimian, "Current Challenges for Visible Light Communications Usage in Vehicle Applications: A Survey," in *IEEE Communications Surveys & Tutorials*, vol. 19, no. 4, pp. 2681-2703, Fourthquarter 2017. doi: 10.1109/COMST.2017.2706940

[13] A.-M. Cailean, and M. Dimian, "Toward Environmental-Adaptive Visible Light Communications Receivers for Automotive Applications: A Review," in *IEEE Sensors J.,* vol. 16, no.9, pp.2803-2811, May 2016, doi: 10.1109/JSEN.2016.2529019

[14] A. M. Căilean, M. Dimian, A. Done, E.-D. Olariu, L.-N. Cojocariu, "Intelligent traffic light enhanced with data transmission capabilities," Patent Applications no. A/00992, 28.11.2017, State Office for Inventions and Trademarks, Bucharest, Romania.

[15] A. K. Saxena and V. Dutta, "A versatile microprocessor based controller for solar tracking," IEEE Conference on Photovoltaic Specialists, 1990, pp. 1105-1109 vol.2. doi: 10.1109/PVSC.1990.111788

[16] A. Yazidi, F. Betin, G. Notton and G. A. Capolino, "Low cost two-axis solar tracker with high precision positioning," 2006 First International Symposium on Environment Identities and Mediterranean Area, Corte-Ajaccio, 2006, pp. 211-216. doi: 10.1109/ISEIMA.2006.344932

[17] M. Zolkapli, S. A. M. Al-Junid, Z. Othman, A. Manut and M. A. Mohd Zulkifli, "High-efficiency dual-axis solar tracking developement using Arduino," 2013 International Conference on Technology, Informatics, Management, Engineering and Environment, Bandung, 2013, pp. 43-47. doi: 10.1109/TIME-E.2013.6611961

[18] E.D. Olariu, M. Jeder, D. Cernomazu, C. Ungureanu, I. Nițan, "Motor solar cu structură intermediară flexibilă de acționare ", Patent Applications no. A/00326/ 05.10.2012, State Office for Inventions and Trademarks, Bucharest, Romania.

[19] C. Ungureanu, C. Bobric and D. Irimia, "Fuzzy logic control of a new type of electromagnetic converter with rolling rotor," *2014 International Conference on Applied and Theoretical Electricity (ICATE)*, Craiova, 2014, pp. 1-4. doi: 10.1109/ICATE.2014.6972602

[20] C. Ungureanu and A. Graur, "A novel design of a rolling rotor actuator with axial air gap," *2014 International Symposium on Fundamentals of Electrical Engineering (ISFEE)*, Bucharest, 2014, pp. 1-6. doi: 10.1109/ISFEE.2014.7050557

[21] Brandon et al., "Low temperature double-layer capacitors using asymmetyc and spiro-type quaternary ammonium salts," US Pattent no. 8804309 B2, Aug. 2014.

[22] J. Zhang, J. Wang and X. Wu, "Research on Supercapacitor Charging Efficiency of Photovoltaic System," *2012 Asia-Pacific Power and Energy Engineering Conference*, Shanghai, 2012, pp. 1-5. doi: 10.1109/APPEEC.2012.6307169

[23] *Traffic Control Equipment—Signal Heads*, Eur. Commitee Standard EN 12368, Apr. 2006.