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RESEARCH ARTICLE

A Single-Stage Smart Driver with Automatic Dimming Capability for Multiple LED Strings Biased from a Single Point

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HIGHLIGHTS

- *A LED driver that can operate at different LED loads which are commercially available on the market has been designed*
- *The purpose of the designed smart driver is to try to extend the lifetime of the LEDs*
- *The requirement for different LED driver designs for different LED loads is eliminated.*

Keywords:

- Light-emitting-diode (LED)
- LED Driver
- Smart Driver
- LED life
- LED array

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GRAPHICAL ABSTRACT

A driver system for high-power light-emitting diodes (LEDs) is presented. The proposed driver system is based on flyback converter topology, and it uses single-stage power factor correction with microcontroller support. The driver has two main parts; a source for an LED array, and a control unit including sensors. Instead of using conventional constant voltage or constant current driver topologies, the proposed system adjusts the output voltage by considering the LED parameters, the number of serial and parallel LEDs on the load array, and the data from sensors. Via the current sensor, the output current is measured at specific periods and limited by the microcontroller according to the LED load. Moreover, the microcontroller can detect an open circuit condition on the LED array by following current changes. A temperature sensor and a light-dependent resistor (LDR) are used to increase the lifetime of LEDs.

Figure A. The designed LED driver

Aim of Article : *This study aims to design a smart LED driver for different LED loads.*

Theory and Methodology : *The designed system is a microcontroller-based smart LED driver. The proposed driver adjusts the output voltage and current according to the LED parameters on the load and the data read from the sensors.*

Findings and Results: *With the designed prototype driver shown in Figure a, measurements were made for different LED loads, and it has been determined that the driver system worked in harmony with different LED loads and changed the output current and voltage values according to the data received from the sensors.*

Conclusion : *With the proposed solution, a smart driver design has been created for commercially available LED PCBs on the market.*

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ABSTRACT

In this study, a driver system for high-power light-emitting diodes (LEDs) is presented. The proposed driver system is based on flyback converter topology, and it uses single-stage power factor correction with microcontroller support. The driver has two main parts; a source for an LED array, and a control unit including sensors. Instead of using conventional constant voltage or constant current driver topologies, the proposed system adjusts the output voltage by considering the LED parameters, the number of serial and parallel LEDs on the load array, and the data from sensors. Via the current sensor, the output current is measured at specific periods and limited by the microcontroller according to the LED load. Moreover, the microcontroller can detect an open circuit condition on the LED array by following current changes. A temperature sensor and a light-dependent resistor (LDR) are used to increase the lifetime of LEDs.

Keywords: *Light-emitting-diode (LED), LED Driver, Smart Driver, LED life, LED array*

I. INTRODUCTION

The LED lighting systems gradually began to replace traditional lighting systems thanks to their high brightness, long life, and high-efficiency features [1]. If this conversion was completed all around the world, the total energy saving would be around 1000 TWh/year [2].

The linear power supply units have around 60% efficiency whereas switch-mode power supplies (SMPS) have more than 80% efficiency. Therefore, most of the LED driver circuits based on the switching mode power supply [3]. In addition to being energy efficient, the expectation from LED driver circuits is increasing day by day. They should have a compact structure, be smart, be dimmable, and support equipment that should allow remote control or connection to the IoT platforms. Moreover, the driver circuits are also expected to meet standards in terms of power factor. The single-stage power factor correction (PFC) technique is widely used to reduce the cost, improve efficiency, and extend the current conduction angle of the LED drivers [4]-[9].

Although manufacturers are capable of driving LEDs at higher currents, 1W power LEDs driven at 350mA are commonly used [10],[11]. In many applications, several series and parallel (n*m) LED strings exist to obtain some design requirements such as voltage, current, and power [8],[12]. However, each LED has different forward voltage drops because of its tolerance, which leads to a huge current difference in parallel strings. Therefore, different current balancing methods have been proposed [13]-[17]. Although these techniques are shown improvements in current balancing, they are currently not suitable for commercially available LED printed circuit boards (PCB), because quite a lot of them consist of several LED strings connected in parallel to a single bias point.

In LED lighting applications, the forward voltage drop on each LED decreases with increasing junction temperature of LED [18],[19]. The reasons for the heating at the p-n junction are the ambient temperature and the ohmic heating at the bandgap which is the most important factor affecting the LED life [20]. The LED life can be defined as the duration that LED can produce sufficient light for the specific application which determines the operating time of lighting armature in hours that the output light regresses 70% of its starting light intensity [21]. Therefore, while adjusting the driver output current, the temperature value should also be taken into account as a parameter.

In this study, a LED driver is proposed which can work at different LED PCBs which are commercially available on the market. Moreover, when an open circuit occurs at an individual string on the LED array, the proposed driver can detect this situation, and adjust the output power according to the new load. With the necessary sensors, temperature and environment light intensity are used as parameters in the calculation of the output power of the driver as well.

II. Principle Of Operation

Providing the longest LED life and efficiency are the two most important features of the LED driver. It is a big challenge for LED drivers to manage output current and output voltage. Many LED driver circuits use either constant current topology or constant voltage topology. They both are not suitable for the load which is mentioned in the previous section. A threshold voltage of a diode depends on temperature. Equation 1 shows the diode voltage which depends on temperature [22]:

$$V(T) = \frac{kT}{e}\ ln\frac{I}{I_S^*} + \frac{E_g(T)}{e} \qquad (1)$$

The first summand shows the Fermi level and the second summand depends on the changes in bandgap energy which generally has a higher effect from the first summand. As the temperature increases, the energy gap decreases; therefore, applying a constant voltage to LEDs, while the temperature increasing, causes a significant current change. Applying a constant current to LEDs, irrespective of temperature results not only in decreasing the emission intensity of LEDs but also for long-term periods decreasing the lifetime of LEDs. Moreover, a simple constant current driver gets no data from the load; if the load is thought of as a combination of LED strings, and the output current of the driver sets to some value which depends on the operating current of one LED times the number of strings, the driver supplies the same amount of current regardless of the recent situation of the load. Any damage on one or more LED strings causes extra current stress on the remaining strings; as a result, the remaining LEDs cannot stand much longer. Because of these drawbacks, the proposed design uses the combination of these two topologies which is to adjust output voltage depending on the LEDs operating voltage and also adjust the maximum output current that the LED array can get and detect any damage on the load.

The temperature of the p-n junction has to be kept under critical values to be able to obtain the longest LED life [20], [23],[24]. There is no chance to measure the exact temperature of the p-n junction; however, measuring the temperature at the closest point to the p-n junction, the T-point of LED [20], would give an idea about the operating temperature. The temperature can be measured periodically by placing a sensor on the aluminum PCB so that the measured value can be included as a parameter to the equation in setting the output power.

Using the LED armature when it is needed has a significant effect on the lifetime of LEDs. By measuring the daylight intensity, the unwanted operating periods can be minimized. The proposed driver uses automatic analog diming which is the

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simplest and cheapest technique is based on changing output voltage value [25].

The proposed system (see Fig.1) is formed from two main parts; the first part is the power circuit (see Fig.2), the second one is the control circuit (see Fig.4).

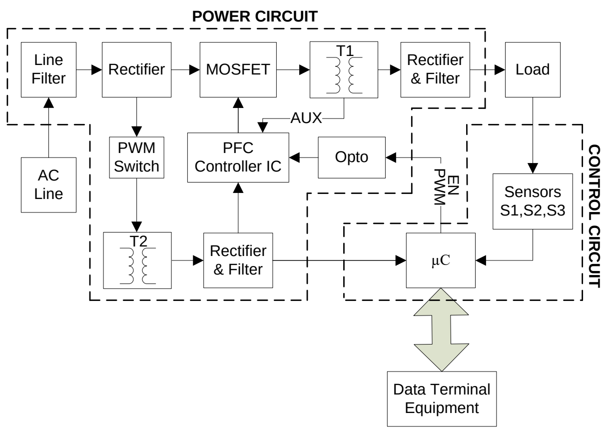

Figure. 1. Proposed Driver System

A. The Power Circuit

The power circuit comprises a line filter, a flyback converter which is the most common converter in low-power LED driver applications because of its simplicity and low cost, and a low-power SMPS which is used to power up the control circuit, and the PFC circuit.

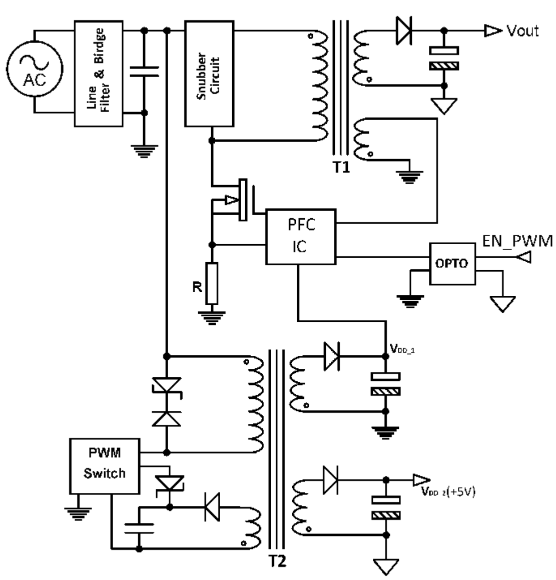

Figure. 2. The Power Circuit

The PFC integrated circuit is designed to work in critical conduction mode (CRM). However, in the proposed driver system because of variable output voltage levels according to LED load, working only at CRM couldn't be enough to get a high-power factor. The driver may not work at full load condition, so the PFC controller has to be controlled as well according to the output voltage. The microcontroller measures the output voltage value continuously and sends a pulse width modulation (PWM) signal to the PFC controller which enables and disables the controller. PWM signal has a fixed frequency but the duty cycle of this signal changes with the required output voltage value, as shown in Fig. 3. If higher voltage values are needed, the duty cycle increases. And with variable on-time & off-time gate signal, the peak inductor current is proportional to the rectified AC line voltage. In this way, the input current waveform follows the input voltage.

By using the second low-power SMPS, the microcontroller can operate independently from the main power supply. Moreover, it also provides a continuous voltage to the PFC IC instead of biasing with a serial resistor from high input voltage after rectifier; thus, an efficient way is chosen which increases the overall efficiency of the driver circuit.

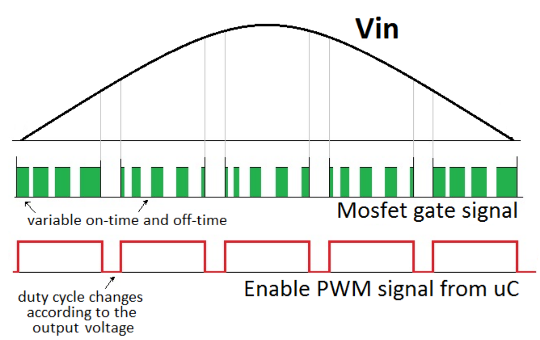

Figure. 3. The Switching frequency variations

If any damage happens at the main power supply such as unwanted voltage rising, the microcontroller turns off the main power supply and protects LEDs. Instead of changing the whole armature including LEDs, changing only the driver is more effective in terms of cost. If any damage occurs at the low power SMPS side, there will be no voltage at the load bias output since the microcontroller cannot operate.

B. The Control Circuit

The block diagram of the control circuit is shown in Fig. 4. The microcontroller is located at the center of this unit and determines the output voltage and current according to the data which are obtained from sensors. The data terminal equipment (DTE) (see Fig.5), which

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is used to provide the parameters such as operating & turn-off voltage, operating current of each LED, number of serial LEDs and number of parallel strings in the array, the maximum and critical operating temperatures of LEDs, is another microcontroller-based system.

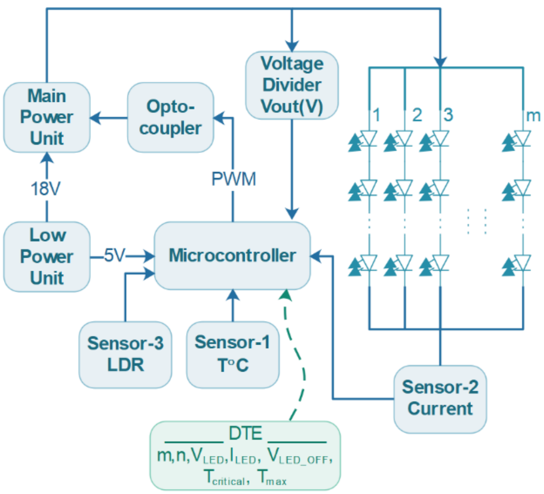

Figure. 4. The Control Circuit

These parameters can be set according to the LED load; thus, the same driver can be used for different arrays, as a result, different driver design requirements for different LED loads could be eliminated.

Figure. 5. Data Terminal Equipment (DTE)

On the other hand, this concept has some limitations; for example, the maximum number of serial LEDs cannot exceed 14 and cannot be under 7, the parallel number of strings cannot exceed 7 and cannot be under 3; these limitations obtained from experiments are used to maximize the efficiency of the driver circuit.

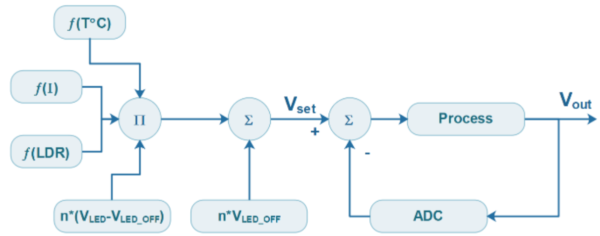

Figure. 6. The set output voltage calculation

According to all these parameters set by the DTE, and the data from sensors, the microcontroller sets the output voltage for the load. The set output voltage, V_{set}, is calculated with the following procedure which is shown in Fig. 6.

$$V_{set} = n * V_{LED\_OFF} + (n * (V_{LED} - V_{LED\_OFF})) * f(sensors) \quad (2)$$

$$f(sensors) = \frac{f(\mathrm{LDR})}{100} * \frac{f(\mathrm{I})}{100} * \frac{f(\mathrm{T°C})}{100} \quad (3)$$

where n is the number of LED in one string in the LED array, V_{LED_OFF} is the minimum operating voltage for one LED, V_{LED} is the proper operating voltage for one LED, $f(\mathrm{I})$, $f(\mathrm{T°C})$, and $f(\mathrm{LDR})$ are the functions of current, temperature, light intensity of the environment affecting the output voltage respectively.

The output voltage is continuously measured by using a voltage divider and a zener diode that is used to protect the input port of the microcontroller for any high voltage ripples. The theoretical value calculated from equations 2 and 3, V_{set}, is compared with the measured value, V_{out}. According to the difference between these two values, the duty cycle of the PWM signal applied to the PFC controller is changed between 0 and 90%.

To maximize the lifetime of LEDs, unnecessary usage of the armature has to be prevented. By using LDR, the turn-on time is spread into five different steps. The factor of LDR on the output voltage is shown with $f(\mathrm{LDR})$ and for the highest environment light intensity, it takes the lowest ratio, for the lowest intensity vice versa; so, the driver gets automatic dimming capability. Another important feature of the driver is that the output voltage starts increasing gradually thanks to the automatic dimming capability, so the instantaneous start-ups which can damage the LEDs can be prevented.

A fully integrated, hall effect-based linear current sensor, ACS712, is used to measure the overall array current. The maximum output current is defined as follow;

$$I_{out(max)} = m * I_{LED} \quad (4)$$

and corresponding output voltage value, V_I, from the current sensor is [26];

$$V_I = m * I_{LED} * 0.185 + 2.5 \quad (5)$$

where m is the number of parallel strings at the LED array, I_{LED} is the current value for one LED. The sensitivity of the ACS712 current sensor is 0.185V/A.

The microcontroller calculates the maximum output current which the load is capable of drawing with equation 4 and checks the real current continuously. If the output current exceeds this maximum value because of any reason, it starts to decrease the set output voltage by the factor of f(I) to protect the LED array. The relationship between measured current (I_{out}) and calculated possible maximum output current (I_{out_max}) is shown below in Fig.7.

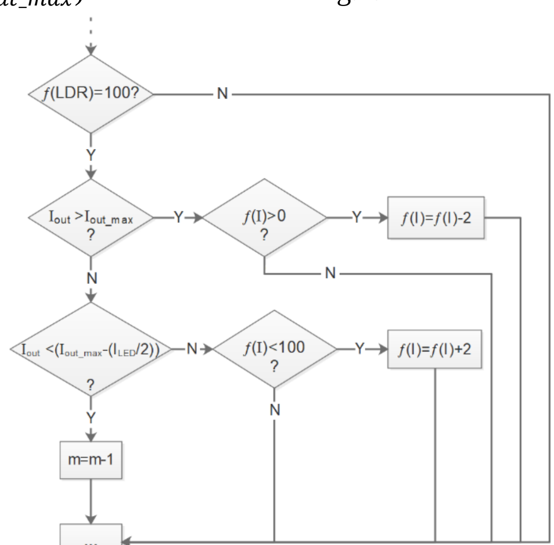

Figure. 7. Current Measurement Algorithm

The proposed driver system can detect any open circuit condition on one or more parallel LED strings. When the load has m strings, and then suddenly the measured current is decreased at least by the half of one string current at the highest f(LDR) and f(T°C), the microcontroller reduces the number of parallel strings (m) and recalculates the maximum output current that the load can handle. For example; if the load has 4 parallel strings, and one of the LED has 0.35A operating current, so the maximum output current (I_{out_max}) would be 1.4 A. When one of the LED on the string has become an open circuit, the output current would decrease to 1.05 A, which means that $I_{out} < \left(I_{out\_max} - \frac{I_{LED}}{2}\right)$ the condition becomes true. So, the driver decides that one of the parallel strings at the load has been damaged, then it decreases "m" by one. The maximum output current of the new load is set, and the microcontroller prepares an error code to send to the DTE if it is required.

One-wire digital thermometer IC, DS18B20, is used as a temperature sensor to measure the temperature on the aluminum PCB where LEDs are placed. When the temperature exceeds the critical value, which is set via the DTE according to the LED characteristics, the output voltage decreases by the ratio of temperature function. The function is calculated from equation 6:

$$f(\text{T°C}) = 100 - \left[(T - T_{critical}) * \left(\frac{100}{T_{max} - T_{critical}}\right)\right] \quad (6)$$

where T is the measured temperature value, $T_{critical}$ is the temperature value that the driver makes an effort to start to decrease, and T_{max} is the maximum temperature value which is not harmful to LEDs. If T_{max} is exceeded, the main power supply is turned off. If the measured temperature is under $T_{critical}$, f(T°C) is set to one hundred.

In addition to the parameter setting functionality of the DTE, it can be also used to read error codes from the driver. These error codes are used to inform the user about the driver to decrease repair time. Error codes:

1. Error Code 0x01: It shows that temperature sensor error. It can happen because of the fault of the temperature sensor or the absence of it.
2. Error Code 0x02: It shows that one or more parallel strings have become open circuits on the LED array.
3. Error Code 0x03: It shows output voltage error.

III. DESIGN EXAMPLE

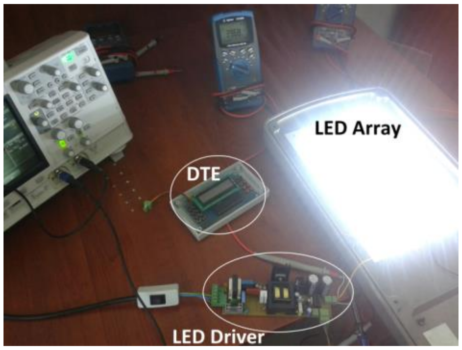

Figure. 8. Application Circuit

To verify the feasibility of the proposed LED driver, the prototype driver is tested. For the first measurement, different LED arrays were used as a load to show efficiency, power factor, and cosφ values. The $T_{critical}$, T_{max}, V_{LED}, $V_{LED_{off}}$, and I_{LED} parameters were set by using DTE to 70°C, 85°C, 3.3V, 2.5V, and 350mA respectively. The input voltage was 220VAC, 50 Hz. The driver was worked at room temperature and the temperature on the LED PCB was under $T_{critical}$ value, so the f(T°C) was at maximum value. The light sensor was covered with black paper to avoid environmental lights. For different n and m values, the operating parameters of the driver are shown in Table 1.

Table I.
Driver parameters for different LED loads

n	m	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{in} (W)	%μ	cosφ	PF
8	5	26.33	1.74	45.81	50	91.6	0.93	0.93
10	6	32.69	2.094	68.45	75	91.2	0.96	0.96
11	5	36.34	1.74	63.23	71	89	0.96	0.96
13	6	43.39	2.125	92.2	104	88.6	0.98	0.98

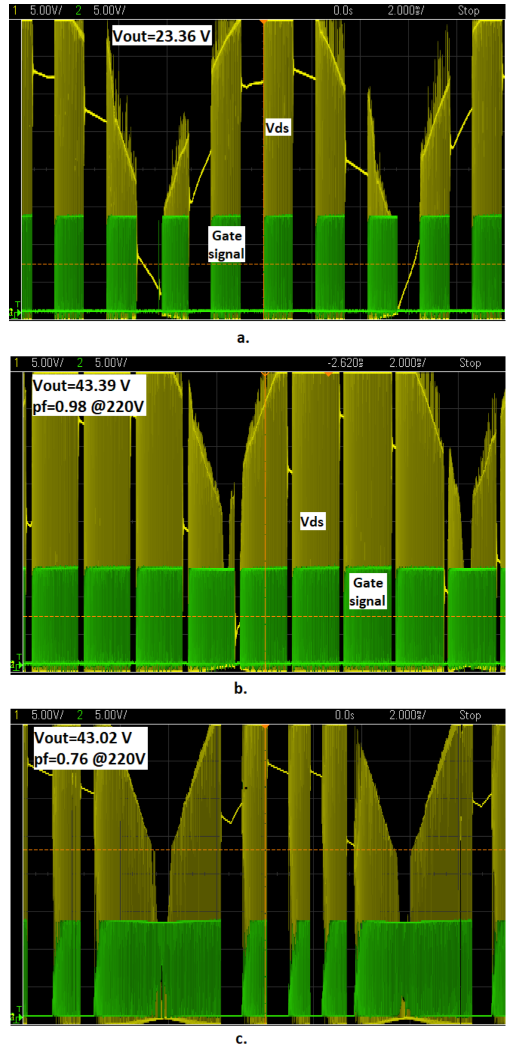

Figure. 9. a) The load is n=7, m=3. **b)** The load is n=13, m=6 with PWM enable signal. **c)** The load is n=13, m=6 without PWM enable signal.

In Fig. 9 a. and b., the differences between MOSFET drain voltage and gate signals are shown for two different output voltage levels; at the lower output voltage level, on-time periods of MOSFET are narrow. The effect of using the PWM signal to activate the PFC controller instead of just sending an on-off signal according to the output voltage values is shown in Fig. 9 b. and c. At graphic b. PWM signal makes the MOSFET conduct in particular periods so the input current which is drawn from the AC line can follow voltage. At the graphic c., the on-off signal without any time control decreases the power factor.

The effect of temperature was shown at the second measurement. The light sensor was covered with black paper. By increasing the ambient temperature, the

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working temperature of the LEDs was forced to increase. In this way, the output power changes could be monitored (see Fig.10). After the critical temperature value, the output voltage started to decrease so the output power. When the temperature reached the maximum value, the main power supply was turned off by the control unit.

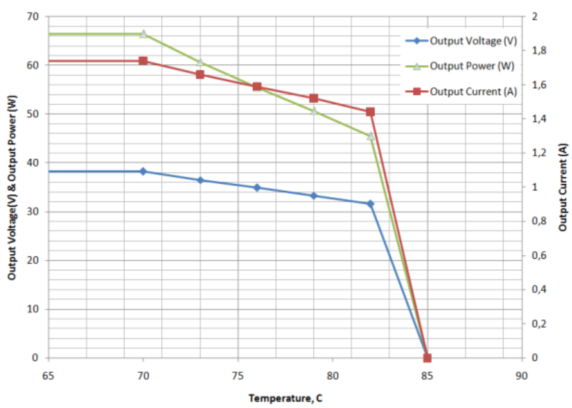

Figure. 10. Temperature vs. Output Power, Voltage & Current

The output voltage starts increasing gradually to prevent instantaneous start-up damages on the LEDs; this situation is shown in Fig. 11.

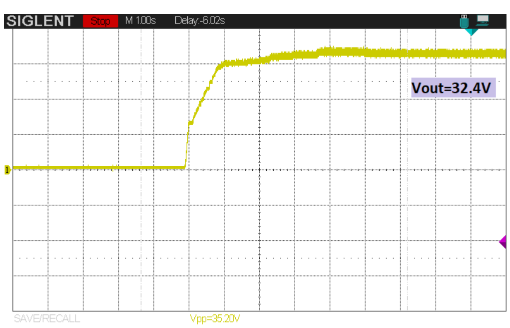

Figure. 11. The driver soft start-up

When the output voltage is 32.4V, the output voltage ripple is 2.8V peak-to-peak which is about 8.6% (see Fig. 12).

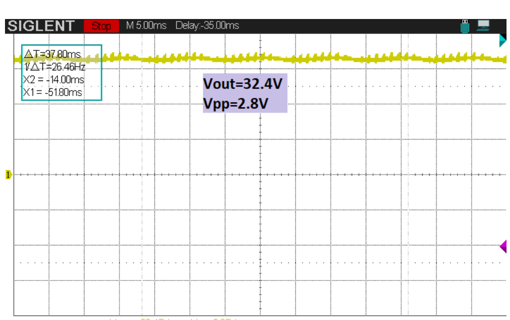

Figure. 12. The output voltage ripple

IV. CONCLUSION

An efficient and smart LED driver system is presented. By controlling the LEDs' temperature, the light intensity, the output current, and the voltage the lifetime of LEDs could be increased. Keeping the operating temperature of LEDs at nominal values is very important to increase the lifetime; therefore, the microcontroller adjusts the output power according to temperature on the LED PCB. Unnecessary usage of LEDs is minimized with LDR to increase efficiency, and the driver gets an automatic dimming capability. The output current is measured continuously and limited as mentioned in LED characteristics. By detecting unexpected current decreases because of an open circuit situation on one or more LEDs, the new maximum output current which load can handle is calculated by the microcontroller, and the new current limit is updated; so any current stress on the remaining LEDs is prevented. However, any short circuit situation on LEDs cannot be detected in this system. The output voltage of the driver is set according to the characteristics of one LED and the parameters of the whole LED strings. By using the DTE which is connected to the driver, the key parameters about LEDs are loaded into the microcontroller so the driver becomes suitable for any load which is in the efficiency limitations of the driver. The DTE also informs the user about the errors which happen at load or the driver itself to minimize repairing time. The next study will be focused on integrating PFC into the microcontroller, adding remote control and data collection properties.

CONFLICTS OF INTEREST

There is no conflict of interest.

RESEARCH AND PUBLICATION ETHICS

The authors declare that this article does not require ethics committee approval or any special permission.

REFERENCES

[1] Y. Wang, J. M. Alonso and X. Ruan, "A Review of LED Drivers and Related Technologies," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 7, pp. 5754-5765, July 2017.

[2] M. R. Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, "Status and Future of High-Power Light-Emitting Diodes for Solid-State Lighting," Display Technology, Journal of, vol.3, no.2, pp.160,175, June 2007.

[3] Yan-Cun Li; Chen, Chern-Lin, "A Novel Single-Stage High-Power-Factor AC-to-DC LED Driving Circuit

With Leakage Inductance Energy Recycling," IEEE Trans. Industrial Electronics, vol.59, no.2, pp.793,802, Feb. 2012.

[4] Moschopoulos, G.; Jain, P., "Single-phase single-stage power-factor-corrected converter topologies," IEEE Trans. Industrial Electronics, vol.52, no.1, pp.23 -35, Feb. 2005.

[5] J. Lee, J. Kwon, E. Kim, W. Choi and B. Kwon, "Single-Stage Single-Switch PFC Flyback Converter Using a Synchronous Rectifier," in IEEE Transactions on Industrial Electronics, vol. 55, no. 3, pp. 1352-1365, March 2008.

[6] Y. Wang, J. Huang, G. Shi, W. Wang and D. Xu, "A Single-Stage Single-Switch LED Driver Based on the Integrated SEPIC Circuit and Class-E Converter," in IEEE Transactions on Power Electronics, vol. 31, no. 8, pp. 5814-5824, Aug. 2016.

[7] B. Poorali and E. Adib, "Analysis of the Integrated SEPIC-Flyback Converter as a Single-Stage Single-Switch Power-Factor-Correction LED Driver," in IEEE Transactions on Industrial Electronics, vol. 63, no. 6, pp. 3562-3570, June 2016.

[8] X. Liu, Q. Yang, Q. Zhou, J. Xu and G. Zhou, "Single-Stage Single-Switch Four-Output Resonant LED Driver With High Power Factor and Passive Current Balancing," in IEEE Transactions on Power Electronics, vol. 32, no. 6, pp. 4566-4576, June 2017.

[9] B. Poorali, E. Adib and H. Farzanehfard, "A Single-Stage Single-Switch Soft-Switching Power-Factor-Correction LED Driver," in IEEE Transactions on Power Electronics, vol. 32, no. 10, pp. 7932-7940, Oct. 2017.

[10] C. Moo, Y. Chen, S. Member, and W. Yang, "An Efficient Driver for Dimmable LED Lighting," IEEE Trans. Power Electron., vol. 27, no. 11, pp. 4613–4618, 2012.

[11] S. Li, S. Tan, C. K. Lee, E. Waffenschmidt, S. Y. Hui and C. K. Tse, "A survey, classification, and critical review of light-emitting diode drivers," in IEEE Transactions on Power Electronics, vol. 31, no. 2, pp. 1503-1516, Feb. 2016.

[12] R. Zhang; H. Chung; "Transformer-Isolated Resonant Driver for Parallel Strings with Robust Balancing and Stabilization of Individual LED Current," IEEE Trans. Power Electron., vol.29, no.7, pp.3694-3708, Jul. 2014.

[13] S. N. Li, W. X. Zhong, W. Chen and S. Y. R. Hui, "Novel Self-Configurable Current-Mirror Techniques for Reducing Current Imbalance in Parallel Light-Emitting Diode (LED) Strings," in IEEE Transactions on Power Electronics, vol. 27, no. 4, pp. 2153-2162, April 2012.

[14] S. Li and S. Y. Ron Hui, "Self-Configurable Current-Mirror Circuit With Short-Circuit and Open-Circuit Fault Tolerance for Balancing Parallel Light-Emitting Diode (LED) String Currents," in IEEE Transactions on Power Electronics, vol. 29, no. 10, pp. 5498-5507, Oct. 2014.

[15] Y. Yu, F. Zhang and J. Ni, "Capacitor clamped current sharing circuit for multi-string LEDs," 2012 IEEE Energy Conversion Congress and Exposition (ECCE), Raleigh, NC, 2012, pp. 3568-3574.

[16] Y. Hu and M. M. Jovanovic, "LED Driver With Self-Adaptive Drive Voltage," in IEEE Transactions on Power Electronics, vol. 23, no. 6, pp. 3116-3125, Nov. 2008.

[17] X. Liu, Q. Yang, Q. Zhou, J. Xu and G. Zhou, "Single-Stage Single-Switch Four-Output Resonant LED Driver with High Power Factor and Passive Current Balancing," in IEEE Transactions on Power Electronics, vol. 32, no. 6, pp. 4566-4576, June 2017.

[18] J. Yeon, D. Kim, K. Cho, and H. Kim, "A single stage flyback power supply unit for LED lighting applications," Electrical and Electronics Engineering, 2009. ELECO 2009. International Conference on, vol., no., pp.I-288, I-292, 5-8 Nov. 2009.

[19] P. S. Almeida, V. C. Bender, H. A. C. Braga, M. A. Dalla Costa, T. B. Marchesan and J. M. Alonso, "Static and Dynamic Photoelectrothermal Modeling of LED Lamps Including Low-Frequency Current Ripple Effects," in IEEE Transactions on Power Electronics, vol. 30, no. 7, pp. 3841-3851, July 2015.

[20] Narendran, N.; Gu, Y., "Life of LED-based white light sources," Journal of Display Technology, vol.1, no.1, pp.167,171, Sept. 2005.

[21] Alliance for Solid-State Illumination Systems and Technologies (ASSIST), ASSIST Recommends: LED Life for General Lighting, Lighting Research Center, vol.1, no.1, February 2005.

[22] E.Fred Schubert, "Light-Emitting Diodes", pp. 104-107, Cambridge University Press, 2003.

[23] Garcia, J.; Dalla-Costa, M.A.; Cardesin, J.; Alonso, J.M.; Rico-Secades, M., "Dimming of High-Brightness LEDs by Means of Luminous Flux Thermal Estimation," IEEE Trans. Power Electron., vol.24, no.4, pp.1107-1114, April 2009.

[24] X. Perpiñà et al., "Thermal Analysis of LED Lamps for Optimal Driver Integration," in IEEE Transactions on Power Electronics, vol. 30, no. 7, pp. 3876-3891, July 2015.

[25] Gacio, D.; Alonso, J.M.; Garcia, J.; Campa, L.; Crespo, M.J.; Rico-Secades, M., "PWM Series Dimming for Slow-Dynamics HPF LED Drivers: The High-Frequency Approach," IEEE Trans. Industrial Electronics, vol.59, no.4, pp.1717,1727, April 2012.

[26] Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Isolation and a Low-Resistance Current Conductor, Allegro microsystems, ACS712 product datasheet, rev.14, pp. 5-9, 2011.