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POWER STAGE AND FEEDBACK LOOP DESIGN OF A FLYBACK CONVERTER FOR POWERING AN ELECTRIC SCOOTER

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Abstract: This document represents a study about designing a power stage and a feedback loop for a Flyback converter – a circuit that is used to charge a battery pack designated for an electric scooter. This converter is designed to supply a 19.5V DC voltage and a maximum of 3.33A at the output of the circuit. The circuit consists of an EMI filter, an RCD Snubber protection circuit, a current mode PWM controller and a feedback loop designed using the TL431 integrated circuit. Its main purpose is to convert a 230V AC voltage to a stable 19.5V DC voltage. The research uses both the mathematical and simulation apparatus to model the behavior of a flyback converter before the physical design procedure. The results obtained will be used as milestones for checking the correct behavior of the real circuit.

Keywords: *Flyback converter, Power stage, CCM operation, DCM operation, Type II Compensation, TL431.*

I. INTRODUCTION

The use of electric scooters has become quite popular over the past few years. They are a good alternative when it comes to going to school or work, so they can be considered a suitable replacement for the more conventional means of transport, such as the personal cars or the buses, especially in big and crowded cities.

Among the advantages of using an electric scooter it can be mentioned: the ease of use, the fact that you do not need a driver's license to drive it and the reduced cost when compared to buying a car.

Of course, there are also some disadvantages when it comes to owning and driving an electric scooter, for example: the lack of a storage space, the problems with the insurance in case of an accident and especially the limited range of the vehicle, which is directly related with the battery capacity.

II. THEORETICAL FUNDAMENTALS

Most electronic circuits used in the industry are based on a DC voltage at the input of the circuit. A DC voltage power supply usually consists of a transformer, a rectifier, an output filter, and a voltage regulator.

The block diagram for a DC voltage source is shown in Figure 1.

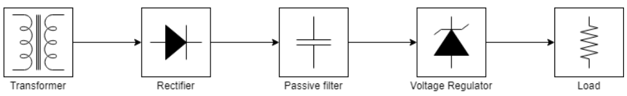

Figure 1. Block diagram of a power supply.

While linear regulators have certain advantages, such as providing a minimum output ripple or that the output voltage is completely independent of certain factors, as for example temperature, they have a major disadvantage - the efficiency.

Mono-alternating rectifiers have an efficiency of approximately 38%. If a bridge rectifier is designed instead, this efficiency increases to approximately 78%, but the average is around 40%.[1]

The switching mode power supplies are much more efficient compared to the previous ones, reaching efficiencies of over 90%. Also, the ratio between the input voltage and the output voltage is insignificant due to the regulating element which operates in the switching mode. The advent of high-speed switching transistors and low-loss ferrites has led to the mass use of this type of power supply since the 1970s. [2]

The flyback converter is a circuit used in switching mode supplies to power electronic devices, such as phones, laptops, etc. The main advantage of using such a converter is that its output is galvanically separated from its input, due to the transformer incorporated directly into the structure of the converter.

Domestic and international standards for power supplies with the input connected to the power network grid require such galvanic isolation from manufacturers. One of the most important advantages is the small size of the transformer, because its size is inverse proportional with the switching frequency of the converter. Therefore, the more the switching frequency of the regulating element is increased, the more the size of the transformer used will be reduced.

The electrical circuit of such a converter is shown in the Figure 2.

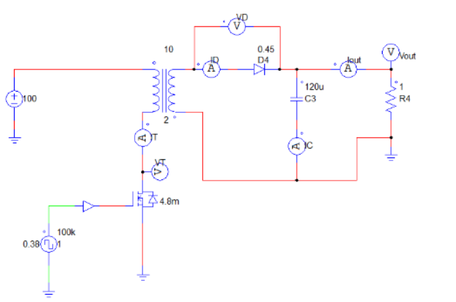

Figure 2. The flyback converter – electrical circuit.

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The Flyback converter can be compared with a Buck-Boost converter. Therefore, all formulas that describe the behavior of the Buck - Boost converter can also be applied to this type of converter.

In steady state we can identify two main modes of operation:

- CCM - Continuous conduction mode
- DCM - Discontinuous conduction mode

The load current for which the converter operates at the limit between the two conduction modes is named I_{SL} - and can be calculated using formula 1:

$$I_{SL} = \frac{U_S * T}{2 * L} * (1-\delta)^2 = \frac{U_S * T}{2 * L} * \left(\frac{U_I}{n * U_S + U_I}\right)^2 \qquad (1)$$

If the current through the coil reaches 0A and maintains this value for a longer time, the circuit works in DCM. Figure 3 shows the waveforms for the two conduction modes. [3]

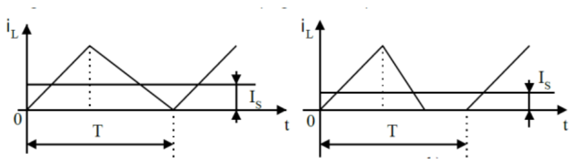

Figure 3. CCM and DCM operation. [3]

In Table 1, advantages and disadvantages of the two conduction modes are presented:

DCM		CCM	
Advantages	Disadvantages	Advantages	Disadvantages
No diode switching losses	Higher output voltage ripple	Lower ripple for the output voltage	A presence of a zero in the right half-plane, which can lead to instability of the system
The inductance of the coil will be lower, which will lead to a smaller transformer	The switching losses on the transistor can be higher because the transistor blocks when its drain-source voltage is at a high value.	Higher value for the RMS output current	The inductance of the coil will be higher, which will lead to a bigger transformer
It is more stable because it has no zero in the right half-plane		Fewer losses in the ferrite core	

Table 1. Advantages and disadvantages of CCM and DCM modes

Another extremely important factor to consider when designing a flyback power supply is the type of feedback loop controller. It can have functions that protect or streamline the designed circuit. Of course, the more functions the controller has, the higher its production cost will be. Some controllers require additional protection circuits, which will lead to larger wiring, while others do not need these protections. Another thing to consider when choosing the type of controller is the conduction mode the converter uses.

In the production of the latest types of controllers, a conduction mode derived from the discontinuous conduction mode is used, namely Valley Switching. It uses a special type of control, which constantly monitors the waveform of the drain-source voltage of the transistor. It changes the switching frequency at which the controller works to reduce the switching losses on the transistor. These losses become significant if the input voltage of the circuit has a high value. The waveforms for the Valley Switching conduction mode can be found in Figure 4.

The controller will operate the MOS transistor when it detects the minimum value of the resonant waveform to reduce losses. The advantages of this conduction mode are listed below:

- Decreased switching losses.
- Decreased current peaks at the CS (current sense) pin of the controller.
- The influence of EMI decreases.

Of course, there are certain disadvantages when using such a conduction mode, including:

- It causes an increase in the voltage ripple at the output of the circuit.
- It is inefficient when the converter operates with low value currents. [4]

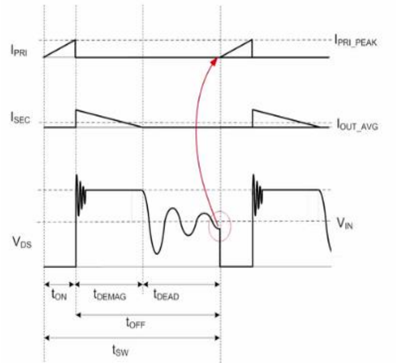

Figure 4. Valley Switching Conduction Mode.[4]

Another conduction mode used in practice is called quasi-resonant conduction and is a transient mode. It can be compared with the Valley Switching conduction, except that the switching is done at the first minimum of the demagnetization time. Therefore, the switching frequency decreases significantly, which leads to an increase in the current capacity of the converter. The waveforms for these types of conduction can be seen in Figure 5. Also, most controllers that use Valley Switching can operate for a short time in quasi-resonant mode.

The advantages of this conduction mode are:

- Maximum possible reduction in switching losses of the MOS transistor.
- Requires a small radio frequency filter.

Unfortunately, this conduction mode has a major disadvantage, namely a control loop that is much more difficult to be implemented compared to the other controllers (requires a significantly higher phase boost). [4]

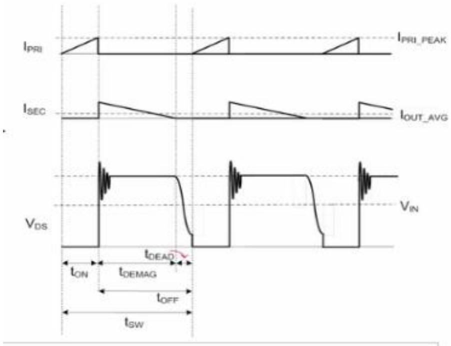

Figure 5. Quasi-resonant Conduction Mode.[4]

One of the most used variants of the compensation loop for a flyback converter consists of a shunt regulator, namely the integrated circuit TL431, and a photocoupler, to keep the galvanic separation advantage.

The TL431 integrated circuit is used in many switching mode power supplies topologies since it can be used as an error compensator. If it is used at low frequencies in conjunction with a resistor and a capacitor, it acts as an integrative amplifier. It has a voltage reference of 2.5V on the inverter input of the amplifier. By means of a resistive divider, the voltage at the output of the power stage is divided in such a way that the value on the non-inverting input is as close as possible to 2.5V.

This circuit is often used together with a photocoupler to further ensure galvanic separation between the input and the output. In this way, any fault that can cause unwanted behavior at the input of the circuit will not affect the output in any way. In a similar way, no unwanted effects from the output will cause problems at the circuit input.

III. IMPLEMENTATION

The block diagram for the simulated circuit is presented in Figure 6.

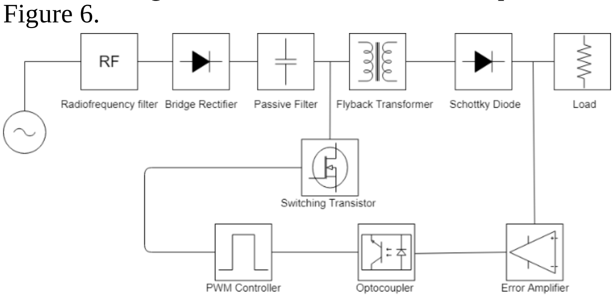

Figure 6. The block diagram of the circuit

The most important choice when designing the power supply is the controller. Depending on which controller we choose, the circuit topology will differ. As previously mentioned, the main conduction modes used by each controller are CCM and DCM. In addition, another thing to consider is how the current in the transformer secondary winding is controlled. The two modes considered for this application are PSR - Primary Side Regulation and SSR - Secondary Side Regulation. The power supply mode for the controllers is similar - the use of a transformer auxiliary winding for the supply voltage.

The first step in designing the power supply is to determine the output power, the efficiency, and the input power. This will be done using the equations (2) and (3).

$$P_{OUT} = V_{OUT} * I_{OUT} \quad (2)$$

where: P_{OUT} is the output power, V_{OUT} is the output voltage and I_{OUT} represents the output current.

This results in a maximum output power of 64.953W.

An achievable efficiency will be chosen, namely 75%.

Based on the output power and efficiency, the input power will be determined:

$$P_{IN} = \frac{P_{OUT}}{\eta} \quad (3)$$

where: η is the efficiency of the power supply.
This results in an input power of 86.58W.

To avoid introducing electromagnetic interference or noise into the network, most switching voltage sources use a radio frequency filter (also called an EMI filter or common mode voltage choke). This filter consists in one or two coils, connected between the supply lines. They may also be accompanied by a filter capacitor and a resistor connected in parallel to the supply lines to ensure that the filter capacitor is discharged when the circuit is not supplied. Class X capacitors are mainly used for the filter.

For the filter capacitor, the European supply standard (195 - 265Vrms) provides a capacity of 1μF / W. Thus, based on the power determined at the input, an electrolytic capacitor of a value close to the calculated one - namely 100μF – will be chosen.

The choosing of the maximum value for the duty cycle will follow. This value should be under the maximum value accepted by the controller, which is 80%. The value 45% has been chosen.

Another parameter to be considered is the switching frequency of the controller. For this application, a controller with the switching frequency of 60kHz will be used.

The output voltage reflected in the primary side of the transformer is determined:

$$V_{RO} = \frac{D_{MAX}}{1 - D_{MAX}} * V_{DC\,MIN} \quad (4)$$

where: D_{MAX} is the maximum duty cycle, V_{RO} is the output voltage reflected in the primary side of the transformer and $V_{DC\,MIN}$ is the minimum voltage on the filter capacitor. The maximum value for the switching transistor $V_{DS\,NOM}$ will be determined using the below formula:

$$V_{DS\,NOM} = V_{RO} + V_{DC\,MAX} = 575.05V \quad (5)$$

The next step is to determine the minimum value for the inductance of the primary side of the transformer:

$$L_M = \frac{(V_{DC\,MIN} * D_{MAX})^2}{2 * P_{IN} * f_S * K_{RF}} = 1.61mH \quad (6)$$

where: L_M – minimum inductance of the primary side, f_S is the switching frequency of the controller and K_{RF} the ripple factor for maximum load and minimum input voltage.

Using this value, the variation of the current through the primary side of the transformer and the peak value for the current flowing through the switching transistor can be determined:

$$\Delta I = \frac{V_{DC\,MIN} * D_{MAX}}{L_M * f_S} = 1.336A \quad (7)$$

$$I_{DS\,PEAK} = I_{EDC} + \frac{\Delta I}{2} = 1.33A \quad (8)$$

where: I_{EDC} is the mean value for the current through the primary and $I_{DS\ PEAK}$ is the peak current through the transistor. To avoid the saturation of the transformer, B_{SAT} will be selected to be equal to 0.35T (where B_{SAT} represents the magnetic flux density saturation value).

Another important parameter for the converter is the RMS value of the current through the transistor ($I_{DS\ RMS}$), which will be determined with equation (9):

$$I_{DS\,RMS} = \sqrt{3 * I_{EDC}^{\,2} + (\frac{\Delta I}{2})^2 * \frac{D_{MAX}}{3}} = 0.517A \quad (9)$$

Based on the previously determined currents and inductance, the minimum number of turns of the primary side of the transformer can be found:

$$N_p = \frac{L_M * I_{OVER}}{B_{SAT} * A_E} = 63.414 \quad (10)$$

where: N_P – the minimum number of turns in the primary side, I_{OVER} is the RMS current through the transistor with an added margin of 10% - to ensure the fact that the transformer will function normally and A_E – the core section area – which can be identified in the datasheet.

Based on the reflected voltage to the primary side and the output voltage we can calculate the turns ratio for the transformer:

$$n = \frac{V_{RO}}{V_{OUT\,MAX} + V_{D\,F}} = 11.812 \quad (11)$$

where: V_{DF} is the forward voltage for the rectifier diode. To find out the number of turns in the secondary N_S, equation (12) will be used:

$$N_S = \frac{N_P}{n} = 5.333 \quad (12)$$

Similar to the way N_S was determined, the number of turns for the auxiliary turn, N_{AUX}, will be calculated, based on equation (13):

$$N_{AUX} = \frac{V_{CC} + V_{D\,F}}{V_{OUT\,MAX}} * N_S = 4.446 \quad (13)$$

where: V_{CC} is the input voltage for the controller.

When it comes to selecting a diode type for the output winding, the best choice is represented by a Schottky diode. Its forward voltage is considerably lower compared to a rectifier diode (0.45 – 0.5V compared to 0.7V). Another advantage is the absence of the recovery time when they switch from the conducting to the non-conducting state, thus they are perfectly suited for high-frequency applications. Thus, the RMS current through the diode and the maximum reverse voltage on the diode will be calculated:

$$I_{D\,RMS} = I_{DS\,RMS} * \sqrt{\frac{1 - D_{MAX}}{D_{MAX}}} * \frac{V_{RO} * K_L}{V_{OUT\,MAX} + V_{D\,F}} = 6.757A \quad (14)$$

$$V_{D\,REV} = V_{OUT\,MAX} + \frac{V_{DC\,MAX} * (V_{OUT\,MAX} + V_{D\,F})}{V_{RO}} = 48.235V \quad (15)$$

When selecting the components, some safety margins must be assured (in this case, a maximum current of 10A and a maximum reverse voltage of 60V).

One of the most important components to determine is the output capacitor. It will influence the output ripple, the output current and the transfer function for the power stage. One of the parasitic components of the capacitor is the ESR (Equivalent Series Resistance). In order to reduce the value of the ESR, we will use 3 capacitors placed in parallel. The equivalent output capacitance will be 3 times higher and the value of the ESR will be divided by 3. So, 3 electrolytic capacitors with an ESR of 18mΩ will be used. The output ripple will be:

$$\Delta V_{OUT} = \frac{I_{OUT\,MAX} * D_{MAX}}{C_{OUT} * f_S} + \frac{I_{DS\,PEAK} * V_{RO} * ESR * K_L}{V_{OUT\,MAX} + V_{D\,F}} = 164\,mV \quad (16)$$

where: C_{OUT} is the total output capacitance and ESR the total value of the equivalent series resistance.

Another important aspect in designing the circuit is represented by the design of a Snubber circuit. This will protect the switching transistor from unwanted voltage spikes. A Snubber circuit represents a passive or active circuit with the specific role of protecting the switching elements in power circuits. In absence of a Snubber, these elements would be exposed to possible dangerous voltage and current spikes that can damage them. These spikes are usually caused by the inductive elements of the circuit. [6]

The power that the Snubber circuit must dissipate will be determined, using equation 17:

$$P_{SN} = \frac{1}{2} * f_S * L_\sigma * I_{DS\,PEAK}^{\;2} * \frac{V_{SN}}{V_{SN} - V_{RO}} = 1.165W \quad (17)$$

where: L_σ represents the leakage inductance and V_{SN} the voltage the Snubber must withstand.

Knowing V_{SN} and P_{SN} the resistance R_{SN} can be calculated, resulting in a value of 190kΩ. The next step is to determine the value of the capacitance C_{SN}, using equation 18:

$$C_{SN} = \frac{V_{SN}}{\Delta V_{SN} * R_{SN} * f_S} = 824nF \quad (18)$$

where: ΔV_{SN} is the ripple of the maximum supported voltage V_{SN}.

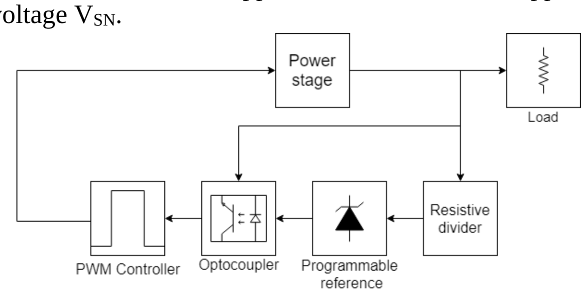

Figure 7. The block diagram for the feedback loop

In conclusion, the most used method in compensating this system is the use of a type 2 compensator. Therefore, by means of a pole and a zero placed in appropriate positions a stable system will be obtained. The assumption will be made that the current transfer factor (CTR) of the optocoupler is 100. The block diagram for the control circuit can be found in figure 7.

The first thing considered when designing the control loop is the conduction mode used, because the transfer function of the power stage will vary depending on the conducting mode chosen. In the case of a small current value, the conduction mode in which the converter will work is DCM. Thus, the presence and influence of a zero in the right half-plane will be avoided, which would cause a limitation in the choice of crossover frequency. For the interrupted driving mode, the transfer function is:

$$H_p = \frac{V_{01}}{V_{FB}} * \frac{(1+\frac{s}{w_Z})}{(1+\frac{s}{w_P})} \tag{19}$$

where: H_P is the transfer function for the power stage, V_{01} is the output voltage, V_{FB} is the voltage in the feedback node and w_Z and w_P are the frequencies of the pole and the zero. These frequencies can be determined:

$$w_z = \frac{1}{ESR*C_{OUT}} \tag{20}$$

$$w_p = \frac{2}{R_L*C_{OUT}} \tag{21}$$

where: R_L is the load for the minimum input voltage and maximum load admitted.

The first step in the design of the compensation circuit is the design of the resistive divider. It is known that the voltage from which the divider is supplied is the output voltage, namely 19.5V. The voltage on the resistor R_B (the one applied to the reference TL431) must be equal to 2.5V. Therefore, the resistances can be determined:

$$R_B = \frac{2.5*R_A}{V_{OUT}-2.5} \tag{22}$$

It should also be mentioned that the value of R_A will have an impact on the response time of the loop, so values up to a maximum of 100kΩ are recommended. If a value of 10kΩ for R_B is chosen, a value of 68.1kΩ will result for R_B. A tolerance as low as possible (preferably ± 1%) is also recommended for these resistances.

Because the zero in the right half-plane does not affect our system, it has no effect on the choice of the crossover frequency. Therefore, we will choose this frequency to be equal to 1 kHz. At this frequency we will have the highest phase boost. The model for this compensation circuit is presented in figure 8.

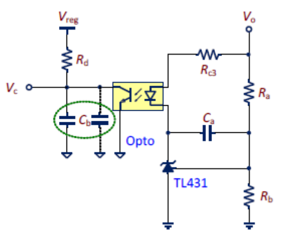

Figure 8. Compensation circuit [7]

It is known that this compensation circuit has a pole in the origin, another pole and a zero. A zero will be place approximately at 500Hz (f_C/2) and the pole at a multiple of f_C (for this application the multiple 2 will be chosen). With the help of the equations (23) and (24), the values for C_A and C_B will be calculated:

$$f_{zero} = \frac{1}{2*\pi*C_A*R_A} \tag{23}$$

$$f_{pole} = \frac{1}{2*\pi*C_B*R_D} \tag{24}$$

Knowing the values of the frequencies (500 Hz and 2 kHz), but also of the resistances (R_A was determined and R_D is the pull-up resistor of the controller), the values for capacitors can be calculated. The value for C_A will be 4.7nF and the value for C_B will be 3.7nF.

Another aspect to be considered is that the photocoupler inserts an additional pole into the transfer function. This pole is represented by a parasitic capacitance called C_{OPTO}, which is placed in parallel with the emitter and the collector of the phototransistor. Therefore, analyzing the behavior of the photocoupler at small signal, the pole introduced by it is at about 8kHz. Based on this, we can deduce that C_{OPTO} is about 995pF. So, the capacitance value for C_B will be 2.8nF.

IV. EXPERIMENTAL RESULTS

To analyze the behavior of the circuit in closed loop, the program PSIM will be used. Because in PSIM the shunt controller TL431 does not have a simulation model and because the controller can only be simulated with a block with one input and one output (ON-OFF Controller component), the control loop with current feedback will be replaced with one with voltage feedback. The parameters of the loop (more precisely the position of the pole and the zero) will remain unchanged, the loop keeping the same frequency response.

To design the compensator circuit, an operational amplifier with negative reaction and 3 passive elements for the reaction are needed. Having already previously determined the values for pole and zero, the determination for the values for C_1, R_2 and C_2 follows.

To illustrate the operation of the circuit, a transient analysis with a duration of 80ms and a simulation step of 50ns will be performed. The circuit was tested under conditions of medium input voltage (value of 325V maximum rectified voltage) and minimum load (load corresponding to an output current of 3.33A). The voltage waveform is shown in Figure 9.

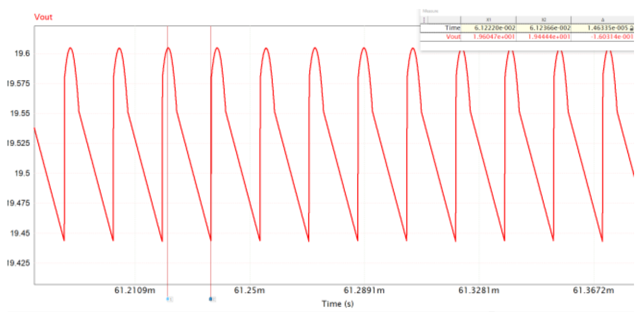

Figure 9. The output voltage of the converter

The next step is to visualize the voltage on the switching element, namely the MOS transistor. This is shown in Figure 10.

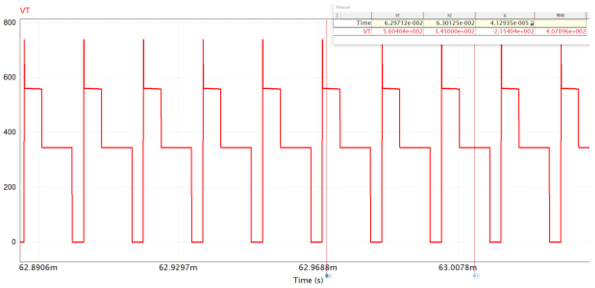

Figure 10. The drain - source voltage on the transistor

The current through the Schottky diode is illustrated in Figure 11.

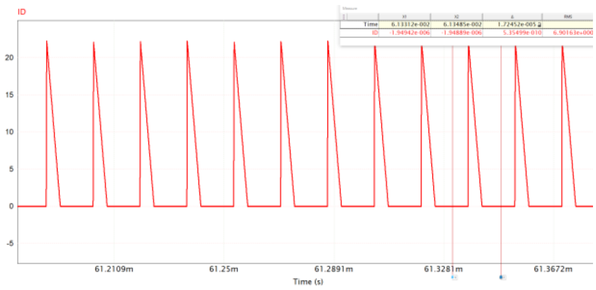

Figure 11. The current through the Schottky diode

In the following figure the reverse voltage drop across the diode is represented.

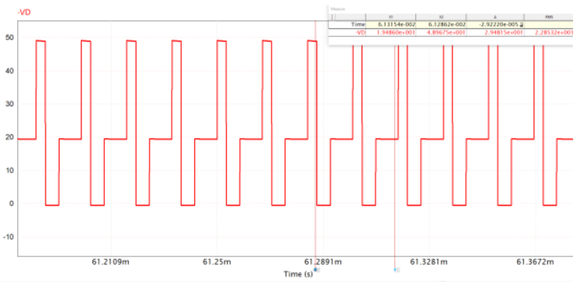

Figure 12. The reverse voltage on the Schottky diode

To perform the simulations, the circuit from the PSIM simulator was adapted to include as many of the variables that appear in the calculations - parasitic resistors, leakage inductors or internal resistances of the diode and power transistor. These parasitic elements cause overvoltage - such as the voltage spike that occurs at the input of the transistor. This value is limited by the Snubber circuit but cannot be canceled completely.

All these aspects were considered in the elaboration of the electrical circuit, of the simulation circuit and in the interpretation of the results. However, there were differences between the calculated and measured values, differences shown in Table 2.

Nr.	Parameter	Calculated value	Measured value
1.	ΔV_{OUT}	164mV	160mV
2.	V_{DS}	575V	560V
3.	$I_{DS\ RMS}$	517mA	541mA
4.	$I_{D\ RMS}$	6.75A	6.9A
5.	$V_{D\ REV}$	48.32V	48.97V

Table 2. Differences between the measured and the calculated values

V. CONCLUSIONS

In conclusion, the above presented circuit serves as an AC to DC converter that can be used to supply constant current and constant voltage to a battery pack used to power an electric scooter. This circuit respects all standards when it comes to the galvanic separation between the primary side and the secondary side of the transformer. The advantage of this power supply is the reduced-price tag compared to other power supplies. For further improvement, one idea would be to modify the feedback loop to also use a voltage feedback loop in addition to the existing current one. Furthermore, some more protection circuits can be added, such as an RC Snubber for the Schottky diode or a DZ Snubber for the switching transistor.

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