SWITCH MODE POWER SUPPLY SCALABILITY

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***Abstract* – As the requirements for electronic inside home appliances are growing, *m*any electronics control boards are being developed to increase the output power.**

A good way to reduce the number of electronic boards developed is using switch mode power supplies, which can delivery a wide range of output power using the same topology. This article presents the study of power supply scalability, changing few components inside the PCB to be used in a wide range of applications.

***Keywords* - EMC/EMI, Scalability, Switch Mode Power Supply and Transformer.**

I. INTRODUCTION

The idea of this development is to have a single board which it is possible to set three different power supplies configurations at the same layout.

This Power Supply will feed an electronic control board, used to control a refrigerator (home appliance). The three configurations differ by only one voltage output, -14V, that must have three different output current levels. The other two outputs have the same current levels.

The reason for this variation on the -14V output is because some products will use DC Fan and others not. Besides, there is the possibility of using two different DC Fans regarding its power (3.6W or 5.5W).

Two of the three voltages outputs are non-insulated and negative and the other one is insulated and positive.

Insulation means no electrical contact to AC mains. The isolated output has a different reference from the other outputs of the SMPS. The non-insulated outputs are referred to the same level as the AC source, so the reference is the same as the phase's AC mains.

This development was made considering a full range AC Mains of 85 to 280 V, 50 and 60 Hz. Voltage output regulation should be +/- 5%, independently of the load state. Maximum and minimum load of each voltage output for all configurations are presented on Table 1.

This power supply should also comply with international standards and operation temperature range of 0°C to 70°C.

Working in partnership with ST Microelectronics, a topology study was performed and the fly-back was chosen, as this topology offers a cheap and easy implementation.

One of the most important parts of a switch mode power supply is the inductor. For the fly-back, in fact, there are coupled inductors, usually called transformer, in spite of its different magnetic behavior. It is responsible for the energy transferring from the primary side of the power supply to the secondary sides, isolated or not.

TABLE I
Output voltage and current configurations

	Output Current	Output Voltage			Total Transformer Output Power
		Non-Insulated		Insulated	
		-14 (V)	-5 (V)	+14 (V)	
Version 1	Minimum Current	0 (mA)	0 (mA)	35 (mA)	5,06 (W)
	Maximum Current	90 (mA)	50 (mA)	200 (mA)	
Version 2	Minimum Current	0 (mA)	0 (mA)	35 (mA)	8,70 (W)
	Maximum Current	350 (mA)	50 (mA)	200 (mA)	
Version 3	Minimum Current	0 (mA)	0 (mA)	35 (mA)	12,20 (W)
	Maximum Current	600 (mA)	50 (mA)	200 (mA)	

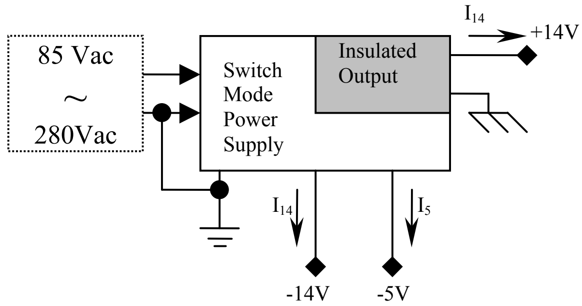


Fig. 1. Diagram block of Power Supply.

As the scope of this development is to have three different configurations, the first thought is to have three different transformers, each one with proper core size, electric parameters, etc. In this case, the project would need to accommodate three transformers at the same layout. To avoid this, the easiest solution could be to use only one transformer (the one for the highest power). This idea helps layout, but generates other problems, such as primary current peak higher for the lower power configurations.

The IC PWM controllers were chosen in a way that they are pin-to-pin compatible and can be changed without layout modifications. Others components have the same scalability.

As the fly-back works in discontinuous current conduction mode (DCM), the transformers design results in EE16, EE20 and EE25 core sizes for the different powers.

The final proposal is to use only the EE20 core, adapting the design to permit the three output powers. The wire diameters were chosen for the highest output current. The device has four windings, the primary and three secondaries. They are accommodated inside the bobbin in way that reduces the leakage inductance and EMC/EMI emission, and give a good magnetic coupling.

II. IMPLEMENTATION

Equation (1) is used to calculate the primary inductance, considering discontinuous current mode.

$$L_P = \frac{V_{\min DC}^{\ 2} \times \delta_{MAX}^{\ 2}}{2 \times f_{sw} \times P_{out}} \times \eta \tag{1}$$

Where:

L_P	- Primary inductance.
V_{minDC}	- Minimum DC Voltage.
δ_{MAX}	- Maximum Duty Cycle.
f_{SW}	- Switching frequency.
P_{out}	- Total Output Power.
η	- Efficiency.

To specify the inductance, Minimum DC Voltage, Maximum Duty Cycle, Switching frequency and efficiency were considered as 120 V, 40%, 60000 Hz and 75%, respectively.

To guarantee the DCM operation, after the calculation of the inductance, the value is reduced in 20% to accommodate the parameters variation in the device production. Table II presents the results.

TABLE II
Primary inductance for all versions

	Version 1	Version 2	Version 3
Primary Inductance	2,86 (mH)	1,66 (mH)	1,18 (mH)
Primary Inductance "Less 20%"	2,2 (mH)	1,3 (mH)	0,95 (mH)

To calculate the wire diameters, it is necessary to know the peak and RMS current of each winding, which can be calculated by equations (2), (3) and (4). Table III presents the results.

$$I_{PK} = \sqrt{\frac{2 \times P_{out}}{\eta \times f_{sw} \times L_P}} \tag{2}$$

$$I_{PKSEC} = \frac{2 \times I_{OUT}}{\delta_{\max diode}} \tag{3}$$

$$I_{RMS} = I_{Peak}\sqrt{\frac{\delta}{3}} \tag{4}$$

Where:

I_{PK}	- Primary peak current.
I_{PKSEC}	- Secondary peak current.
I_{out}	- Secondary current output.
$\delta_{MAX\ DIODE}$	- Maximum duty cycle of diode.
I_{RMS}	- RMS current.
I_{PEAK}	- Peak current.
δ	- Maximum duty cycle

TABLE III
RMS current in all windings

	Primary Winding RMS Current	-14 (V) RMS Current	-5 (V) RMS Current	+14 (V) RMS Current
Version 1	117 (mA)	147 (mA)	82 (mA)	327 (mA)
Version 2	199 (mA)	572 (mA)	82 (mA)	327 (mA)
Version 3	276 (mA)	980 (mA)	82 (mA)	327 (mA)

Once the RMS currents of the windings are defined, with a current density of 400 (A/cm^2), it is possible to determine the wire diameter for each winding, as seen in table IV.

TABLE IV
Wire diameter for all windings

	Primary winding diameter	-14 (V) winding diameter	-5 (V) winding diameter	+14 (V) winding diameter
Version 1	32 (AWG)	31 (AWG)	33 (AWG)	27 (AWG)
Version 2	30 (AWG)	25 (AWG)	33 (AWG)	27 (AWG)
Version 3	28 (AWG)	23 (AWG)	33 (AWG)	27 (AWG)

To finish the device design, the next step is to calculate the number of turns of each winding. For the primary, equation (5) will be used, and for the secondaries, equation (6).

$$N_P = \frac{L_P \times I_{PK}}{Ae \times B_{MAX}} \tag{5}$$

Where:

N_P	- Primary number of turns.
Ae	- Effective core area.
B_{MAX}	- Maximum magnetic flux density of core.

$$N_{Sn} = \frac{N_P \times (V_{OUTn} + V_D) \times (1 - \delta_{MAX})}{V_{\min DC} \times \delta_{MAX}} \tag{6}$$

Where:

N_{Sn}	- Number of turns at "*n*" secondary.
N_P	- Number of turns at primary.
V_{OUTn}	- Output Voltage at "*n*" secondary.
V_D	- Forward Voltage of output diode.

Transformer drawing was prepared using an EE20 core and a bobbin with 10 pins. As there are safety requirements, the minimum distance between insulated pins and non-insulated pins is 8 mm.

This transformer will be constructed in order to accommodate all versions in one device, and it will use the parameters of version 3.

The next figures, 2, 3 and 4 will present the bobbin drawing, electrical diagram and assembling diagram respectively.

Primary inductance is 1,1mH +- 10%. The acceptable leakage inductance is 5%, or <50uH. SEC3 winding shall be constructed using a triple insulation wire, such as TEX-E from Furukawa. The voltage withstanding should be 3000V for 2 seconds between all winding and core.

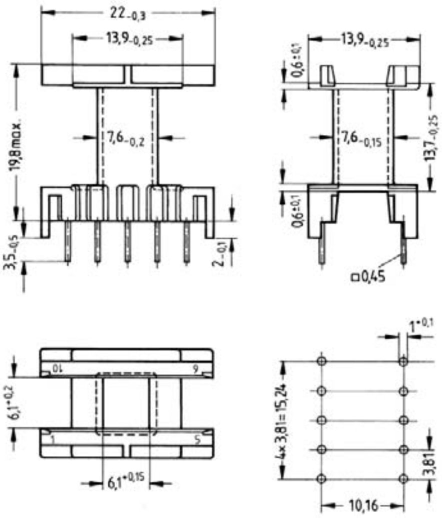


Fig. 2. Bobbin Drawing for EE20 core.

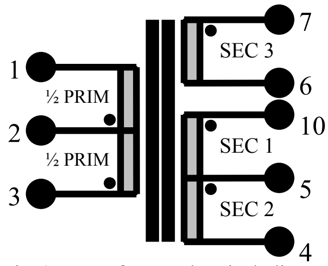


Fig. 3. Transformer electrical diagram.

Considering a half wave rectifier, the equation (7) will be use to calculate the total input capacitance, considering a voltage ripple of 30V and a frequency of 60Hz at the input stage, Table V shows the results as well the commercial values chose.

Full schematic of Switch Mode Power Supply can be checked at figure 5.

$$C_{in} = \frac{2 \times E}{V_{\min DC}{}^2 - \left(V_{\min DC} - V_{Ripple}\right)^2} \quad (7)$$

Where:

C_{in} - Input capacitance.
E - Energy.
V_{Ripple} - Ripple Voltage.

TABLE V
Input Capacitance

	Version 1	Version 2	Version 3
Calculated Capacitance	35,6 (uF)	61,3 (uF)	85,9 (uF)
Chose Capacitance	1 x 10 (uF) 1 x 22 (uF)	1 x 33 (uF) 1 x 33 (uF)	1 x 33 (uF) 1 x 47 (uF)

In order to minimize the EMI issues, differential mode filters were introduced in the schematic.

The filter configuration is a 150nF X2 capacitor and a "Pi Filter" with two electrolytic capacitors and an inductor of 220uH.

The feedback is based on a TL431 IC, which is a constant voltage reference of 2.5 (V). Using this IC, it becomes possible to feedback a negative voltage level to the IC. As the PWM Controller IC, VIPer x2 family requires a current injection feedback instead of voltage level, using standard PNP transistor the voltage level is changed to a current level feedback.

The conventional fly-back topology was modified in order to minimize the transformer construction. The MOSFET is referenced to -14V output voltage instead of to the electrolytic capacitor negative pin. In this way, the primary current flows through the secondary winding. The current on primary side has a negative level.

These modifications allow the reduction of auxiliary winding that is intended to supply PWM IC. As the IC reference pin is connected to the -14 V voltage, a small diode is connected to the zero level (negative pin of electrolytic capacitor - Vdd) generating +14 (V), that supplies the PWM IC. Also a small electrolytic capacitor is used in this IC pin to take the average voltage.

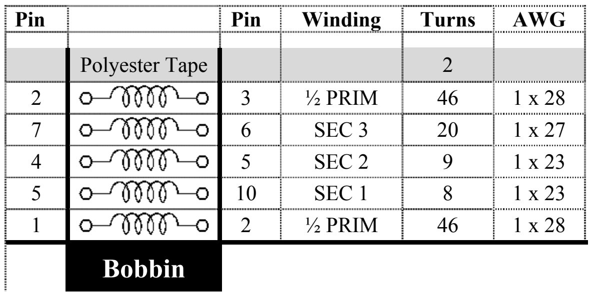


Fig. 4. Transformer winding assembling diagram.

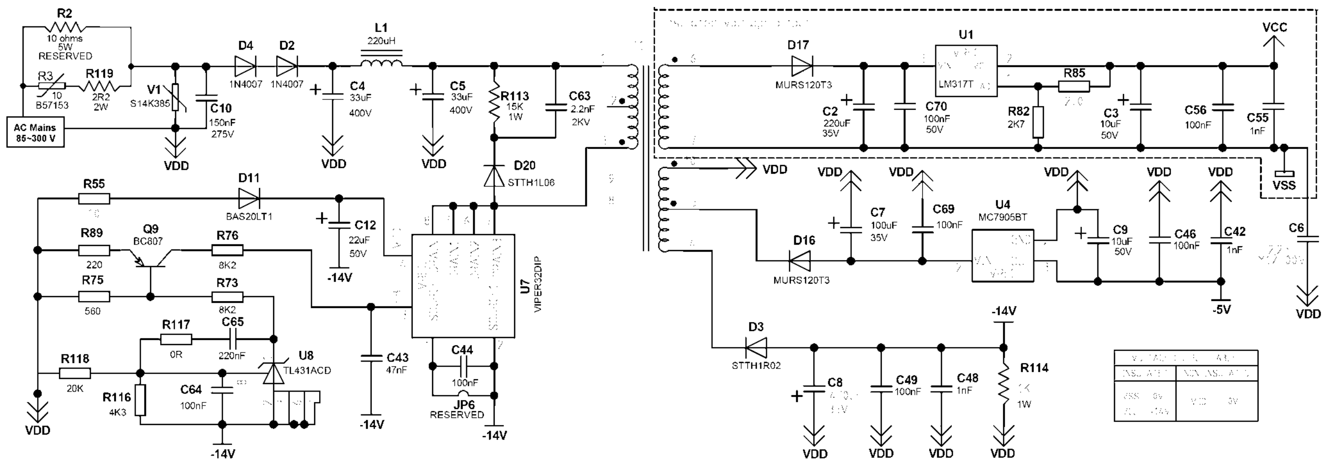


Fig. 5. SMPS full schematic

III. EXPERIMENTAL RESULTS

All tests were performed considering the changing of few components, PWM IC, input and output electrolytic capacitors and the In-rush current limitation.

The next graphs, show the cross regulation in the voltage outputs considering, AC Mains and Load variations for all three versions.

Due to the linear voltage regulator at -5V non-insulated and +14V insulated, the voltage regulation showed at the next graphs will be the voltage input of the regulators.

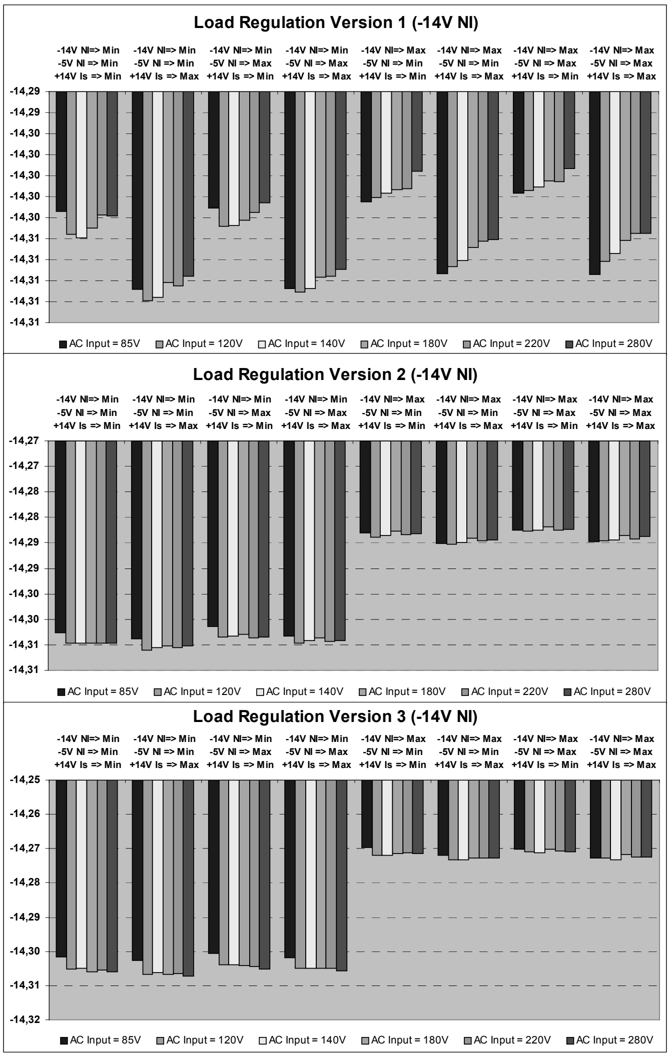
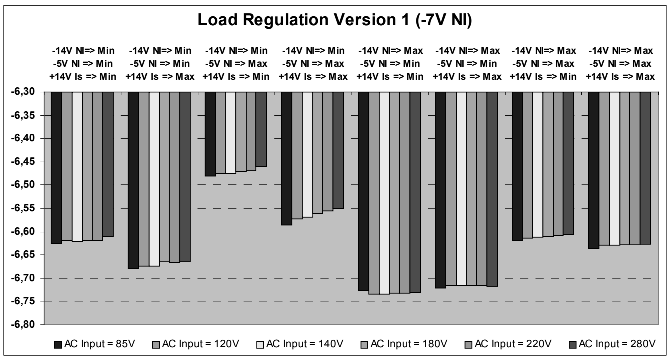


Fig. 6. –14V Non Insulated voltage output cross regulation.



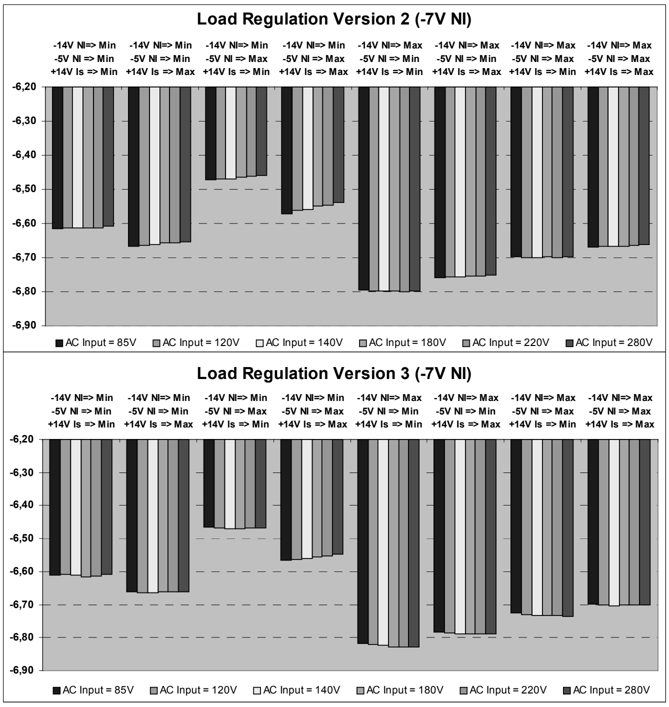


Fig. 7. –7V Non Insulated voltage output cross regulation.

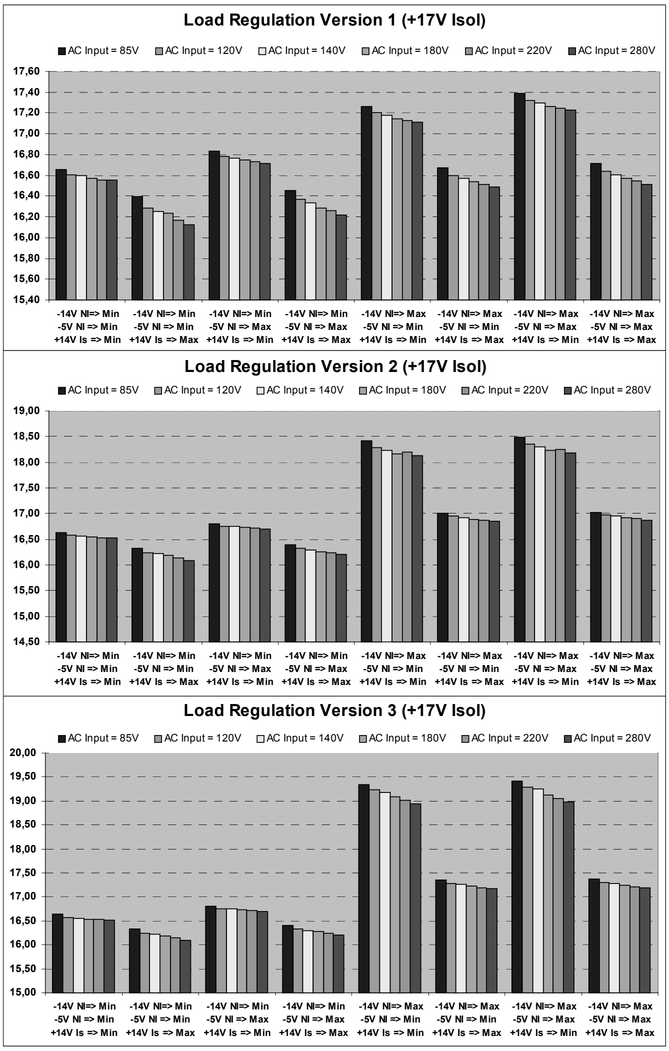


Fig. 8. +17V Insulated voltage output cross regulation.

The next figures, present voltage waveforms of the MOSFET and primary current for different AC Mains voltages and maximum load for all 3 versions.

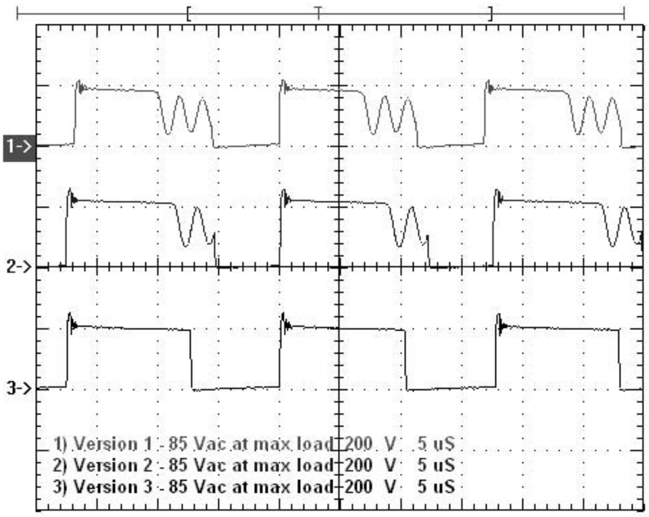


Fig. 9. AC Mains=85V with minimum load.

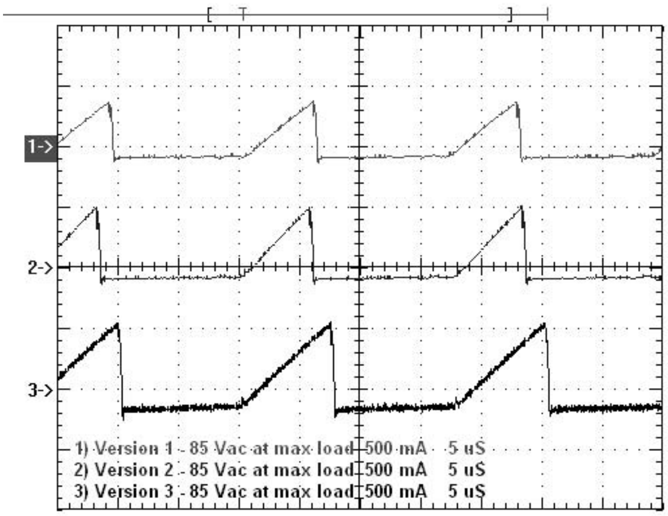


Fig. 10. AC Mains=85V with maximum load.

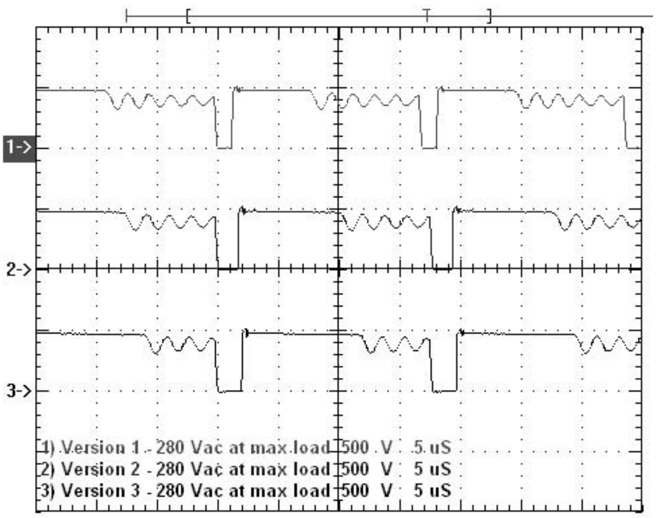


Fig. 11. AC Mains=280V with minimum load.

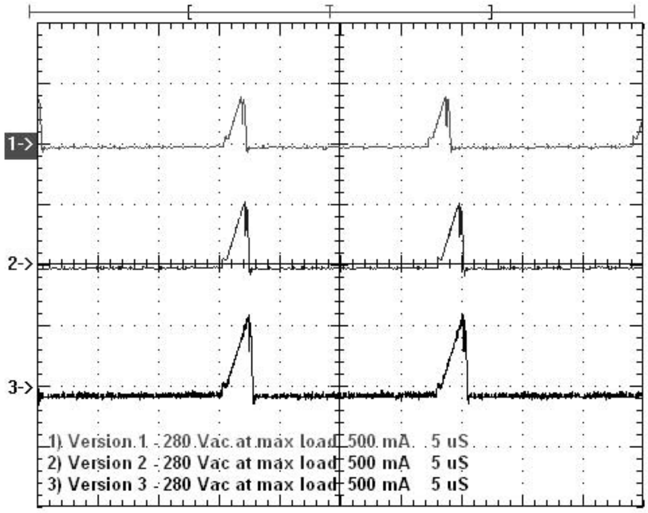


Fig. 12. AC Mains=280V with maximum load.

To better consider the behavior of the voltage in the input side of the voltage regulators, figure 13 shows the power supply efficiency considering different AC Mains and all versions.

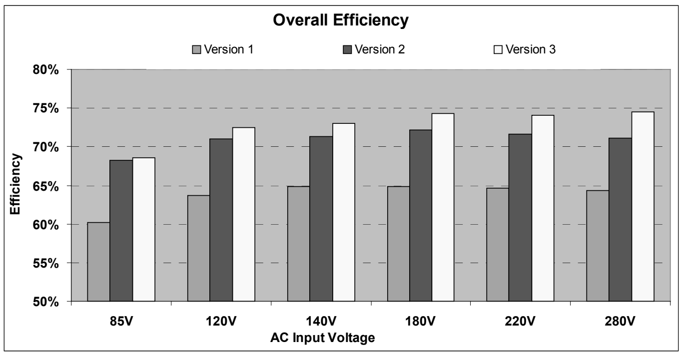


Fig. 13. Version 2 efficiency.

The following figures show the graphs of the conducted emission according to CISPR22 class B in the original schematic of power supply version 2. To perform measurements, quasi-peak and average detectors were used.

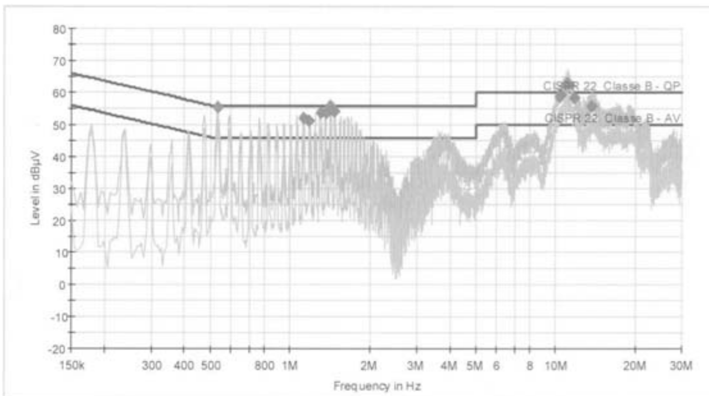


Fig. 14. 127 (V) product – Phase measurement.

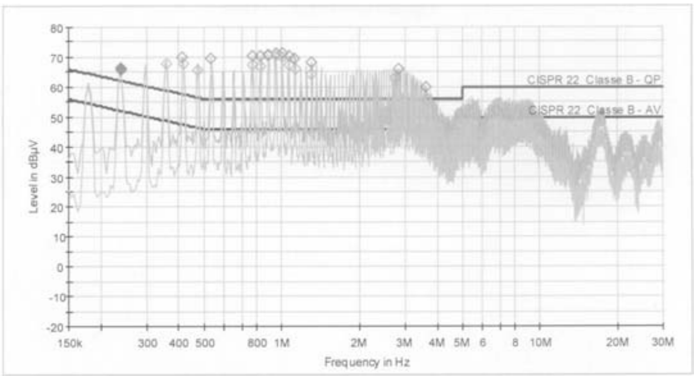


Fig. 15. 220V product – Phase 1 measurement.

Graphs above show that product is not approved by CISPR 22 class B, due to several frequencies with higher values of quasi-peak and average measurements.

A lot of experiments were performed in order to understand and solve this EMI issue. The solution for EMI issue was to add a magnetic shielding in the transformer, a common mode filter made by an 1mH inductor between the negative connection of the electrolytic capacitors at the input, a differential mode filter made by two Y2 capacitors connecting both line and neutral to ground and a 400uH inductor made by ferrite core at the product ground wire. Also the inductor of the input should be changed from 220uH to 1mH.

Figure 16 shows the final measurements with EMI filters.

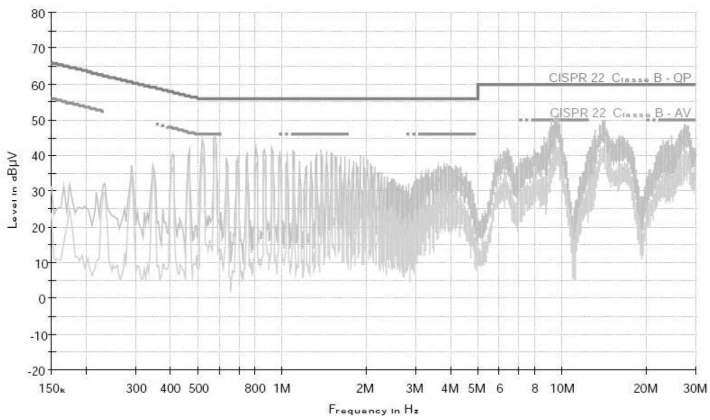


Fig. 16. 220 (V) product – Phase 1 measurement with final version of EMI filter.

IV. CONCLUSION

During the development a adjust was made in the transformer winding in order to reduce the power dissipation at the voltage regulator and efficiency increasing of SMPS. The overall efficiency is acceptable once it is close of the calculated.

The proposal of only one transformer introduced a primary peak current increasing for the version 1 and 2. In terms of version 1 no big penalties but for the version 2, the penalty was the changing of IC. Considering the version 3, the penalty is the working of SMPS at current continuos mode when the AC Mains is low.

The regulation of the –14V is very good. The –7V output have a good regulation due to the winding configuration, made as a tap of the –14V winding. It was observed a 0,37V voltage variation considering AC Mains, load and versions (1, 2 and 3). The insulated output, +17V presented a worse regulation, 3,32V voltage variation considering AC Mains, load and versions. This higher variation is explained by the winding assembling that provides a poor coupling between the windings and core.

The use of only one transformer for a power supply with more than one configuration is possible and for sure reduce the time to market of new electronic boards with the same voltage output levels as well the cost of development, specially the cost of certification. These approach of only one transformer reduces the certification cost to one-third, once no more three transformers should be developed.

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