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Wide Voltage Range Tesla SMPS

da Silva, Fábio Pereira[1]*

Abstract

This WVR-SMPS (Wide Voltage Range Switching Mode Power Supply) or simply Tesla SMPS is a wide range and high voltage input for low power embedded systems. This device allows input voltage as low as $100\ V_{AC}$ and as high as $820\ V_{AC}$ in wide frequency range $(45-450\ Hz)$ or even in DC voltage as low as $142\ V_{DC}$ and as high as $1,160\ V_{DC}$

This white paper will show a detailed description and functionality of this circuit. There are only three active elements provinding control, oscillation, positive and negative feedback, short-circuit protection, overload and under-voltage protection.

Keywords
High voltage — SMPS — Tesla SMPS — Wide Range Power Supply — Embbed Power Devices

[1] *Self-taught Engineer, Self-taught Physicist, Self-taght programmer, Hobbyst, Linux Lover, Crypto Lover and Libertarian*
***Corresponding author e-mail**: fabioegel@gmail.com
moto: Veritas lux mea

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Introduction

This device called Tesla SMPS is a wide input voltage range suitable for embedded devices, such as: Sensors, IoT, measurements, embedded control systems.

It's simply based Flyback topology using only discrete components. In this paper I will show how to build and detailed description for this device that use three active elements only. With three active elements, it's possible to supply any low power embedded device with wide voltage and frequency range and so you can use it at any industrial and home application devices

1. Motivation

I was thinking what could I do to build and design my 8bit Embedded System and any other IoT devices to work at widely universal automotive and home and industry standard voltage into a single system. So I decided to design by myself this device that I called Tesla SMPS using recycled materials

I worked about 3 (three weeks) to design this device and one and half years to improve and fix some problems. After all tests and improvements I've found these results below:

1. Supply for low power Embedded System $(max.\ power\ 20W)$
2. Safe high insulation for output voltage $(max.\ 2,600V)$
3. Limited inrush current $42.6\,A$ @ $1,160\,Volts\ DC$ $(0.38A^2s)$
4. High frequency range in AC operation $(45-450Hz)$
5. AC/DC operation
6. Static short circuit/overload protection
7. Under voltage protection
8. Low cost components $(only\ 3\ active\ elements!)$
9. Startup circuit
10. Limited I_D (current drain) monitor
11. Secondary side grounded for security

2. Methods and why 25.8 Volts?

My first prototype was designed to drive a load with an output voltage of 5 *Volts* and drive a maximum load of 10 *Watts*, but I had found one problem.

Due to high current drop in diode and high peak current the efficiency was lower than 60% and the maximum power was 6 *Watts* only instead of desired 10 *Watts*.

Using 4 principles of Physics in this circuit I had found an equation to find a good output voltage for maximizing efficiency at full load.

To design the entire circuitry and find a better efficiency at full load the 4 basic principles used are:

1. *Faraday's Law*
2. *Law of Conservation of Energy*
3. *Lenz's Law*
4. *Ampère's Law*

Using all principles of Physics above I had designed and I had found a good efficiency for the entire cicuitry. Analysing Flyback topology in Figure 1.

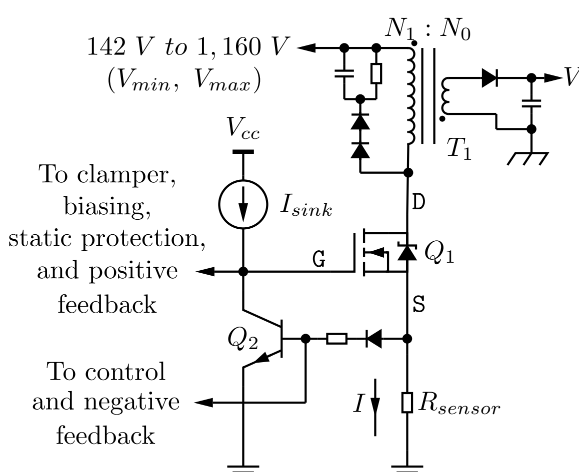

Figure 1. Flyback topology in my Tesla SMPS

Let:

- I ⇒ the maximum current peak
- V_{min} ⇒ the minimum voltage of the input circuit
- V_{max} ⇒ the maximum voltage of the input circuit
- V_1 ⇒ input voltage
- V_0 ⇒ desired output voltage
- N_0 ⇒ number of turn in secondary coil
- N_1 ⇒ number of turn in primary coil
- P_{min} ⇒ minimum output power
- P_{max} ⇒ maximum output power
- T ⇒ time period of switching
- T_{on} ⇒ time period on
- T_{off} ⇒ time period off
- D ⇒ duty cicle
- L ⇒ inductance of the primary coil
- η ⇒ estimated power efficiency

From *Faraday's Law*[1] we get:

$$LI = V_1 T_{on} \tag{2.0.1}$$

From *Law of Conservation of Energy*[2] we get:

$$V_1 T_{on} = V_r T_{off} \tag{2.0.2}$$

Where V_r is a reflected output voltage at primary coil when power transistor Q_1 is turned off. V_r value is:

$$V_r = V_0 \frac{N_1}{N_0} \tag{2.0.3}$$

Replacing Equation 2.0.3 into Equation 2.0.2 we get:

$$\frac{T_{on}}{T_{off}} = \frac{V_0}{V_1} \times \frac{N_1}{N_0} \tag{2.0.4}$$

and

$$D = \frac{1}{1 + \frac{V_1 N_0}{V_0 N_1}} \tag{2.0.5}$$

We know that the average power for a peak current I is:

$$P = \frac{1}{T} \times \frac{LI^2}{2} \tag{2.0.6}$$

Replacing Equation 2.0.1 into Equation 2.0.6 we get:

$$P = \frac{1}{T} \times \frac{V_1 T_{on} I}{2} \tag{2.0.7}$$

We know that:

$$T_{on} = DT \tag{2.0.8}$$

Replacing Equation 2.0.8 into Equation 2.0.7 we get:

$$P = \frac{V_1 I}{2\left(1 + \frac{V_1 N_0}{V_0 N_1}\right)} \tag{2.0.9}$$

We put an η (an estimated efficiency of 65%) to adjust 2.0.9 so, the final equation to find a better voltage and a good circuit synthesis is based in this formula based on 4 Physical Principles Laws:

$$\boxed{P = \frac{\eta V_1 I}{2\left(1 + \frac{V_1 N_0}{V_0 N_1}\right)}} \tag{2.0.10}$$

I made some interaction between coil ratio. Given values for 2.0.10 are:

$$I = 933\ mA$$

$$V_{min} = 142\ Volts$$

$$V_{max} = 1,160\ Volts$$

$$V_0 = 25.8\ Volts$$

$$N_0 = 4\ Turns$$

$$N_1 = 30\ Turns$$

$$\eta = 0.65$$

Replacing into Equation 2.0.10

$$P(V_{min}) = \frac{0.65 \times 142\ Volts \times 933\ mA}{2\left(1 + \frac{142\ Volts \times 4\ Turns}{25.8\ Volts \times 30\ Turns}\right)} = P_{min}$$

So

$$\boxed{P_{min} \approx 24.83\ Watts}$$

And

$$P(V_{max}) = \frac{0.65 \times 1,160\ Volts \times 933\ mA}{2\left(1 + \frac{1,160\ Volts \times 4\ Turns}{25.8\ Volts \times 30\ Turns}\right)} = P_{max}$$

So

$$\boxed{P_{max} \approx 50.28\ Watts}$$

Now we need to know about the maximum voltage in V_D (voltage drain). The limitings factors for transistor are:

1. Switching frequency f
2. Maximum drain voltage V_D
3. Maximum current drain I_D

Calculating f_{max} and f_{min} switching frequency

To calculate frequency f let's use Equation 2.0.1 and 2.0.8 then:

$$T = \frac{LI}{DV_1} \tag{2.1.1}$$

$\therefore$

$$f = \frac{DV_1}{LI} \tag{2.1.2}$$

$$\boxed{f = \frac{V_1}{\left(1 + \frac{V_1 N_0}{V_0 N_1}\right) LI}} \tag{2.1.3}$$

With $L = 1.1\ mH$ and replacing all values in Equation 2.1.3 we get a maximum frequency at full load:

$$f_{max} = \frac{1,160\ Volts}{\left(1 + \frac{1,160\ Volts \times 4\ Turns}{25.8\ Volts \times 30\ Turns}\right) \times 1.1\ mH \times 933\ mA}$$

$$\boxed{f_{max} \approx 161.59\ kHz}$$

and

$$f_{min} = \frac{142\ Volts}{\left(1 + \frac{142\ Volts \times 4\ Turns}{25.8\ Volts \times 30\ Turns}\right) \times 1.1\ mH \times 933\ mA}$$

$$\boxed{f_{min} \approx 79.80\ kHz}$$

Calculating $V_{D_{max}}$ and $V_{D_{min}}$

For calculating maximum voltage in transistor drain (V_{DS})it is necessary to know the voltage in rectified rail (V_{DC} bus) and the reflected voltage of the output voltage (V_r) and (V_0).We know that:

$$\boxed{V_{DS} = V_r + V_{DC}} \tag{2.2.1}$$

where:

$$\boxed{V_{DS} = V_0 \frac{N_1}{N_0} + V_{DC}} \tag{2.2.2}$$

Replacing Equation 2.2.2 with given values we get:

$$V_{DS_{max}} = 25.8\ Volts \times \frac{30\ Turns}{4\ Turns} + 1,160\ Volts$$

$$\boxed{V_{DS_{max}} = 1,353.50\ Volts}$$

and

$$V_{DS_{min}} = 25.8\ Volts \times \frac{30\ Turns}{4\ Turns} + 142\ Volts$$

$$\boxed{V_{DS_{min}} = 335.50\ Volts}$$

Choosing the transistor

I had found a good transistor $2SK1317$ from Renesas website[1] for this application.

In the Table 1 below we can see some characteristics from Renesas datasheet.

Table 1. 2SK1317 Main Characteristics (max. ratings)

	Value	Units
V_{DS}	$1,500$	V
I_D	2.5	A
$Frequency$	> 200	kHz

Analyzing Equation 2.0.10

Analyzing Equation 2.0.10 we can see advantages such as:

1. **Increase output power** at same range of input voltage
2. **Decrease mean current** in schottky diode and increase eficiency of my Testa SMPS
3. **Easy regulation** with higher power
4. **Post regulation**. Using step-down or step-up circuit regulators this voltage can be easily regulated as low as 3.3 V or 5 V. Standard voltages for microcrontrollers such as Arduino, Raspberry Pi, or as high as 50 V for others purposes.

3. Measurements and results

As you can see the results shown in Figure 2 is not acceptable.

After improvements and new re-design of my Tesla SMPS using Equation 2.0.10, new good results and characteristics are shown in Table 2.

[1] Renesas 2SK1317 datasheet

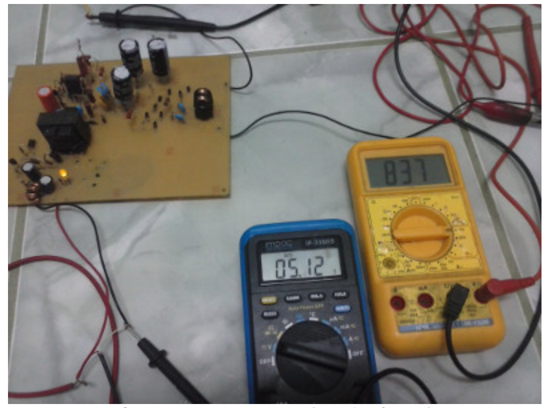

Figure 2. My first prototype testing before improvements:

$$Input\ voltage:\ 837\ V_{AC}\ @\ 60\ Hz$$
$$Output\ voltage:\ 5.12\ V_{DC}/6\ W$$

We can also see the measurements in my osciloscope in Figures 3 and 4 below after re-design and improve my Tesla SMPS:

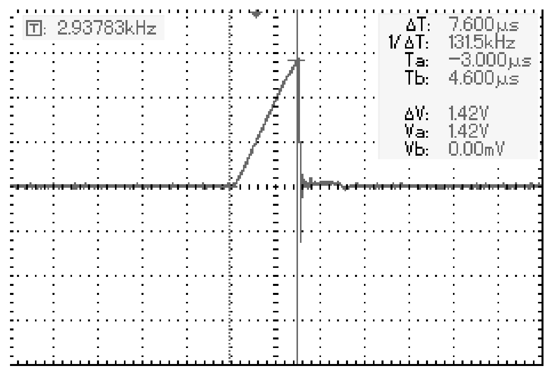

Figure 3. Peak current $I = 946\ mA$ with $R_{sensor} = 1.5\ \Omega$

$$(500\ mV/DIV)$$
$$(5\ \mu s/DIV)$$

Now, with only 3 (three) transistors we can control current, positive and negative feedback, overload and short circuit in primary coil. No integrated circuit is needed to do all this operation. Main focus here is to prove and build with only active and passive elements a very high range input SMPS with recycled materials. Good and acceptable results were found in my project.

Analyzing Figure 4 we can see the control circuit waveform at power transistor gate (V_{GS}). It's quite different as we expected and you expected a square wave but it's waveform makes sense. Let's analyze it step by step.

First of all let's see Figure 1.

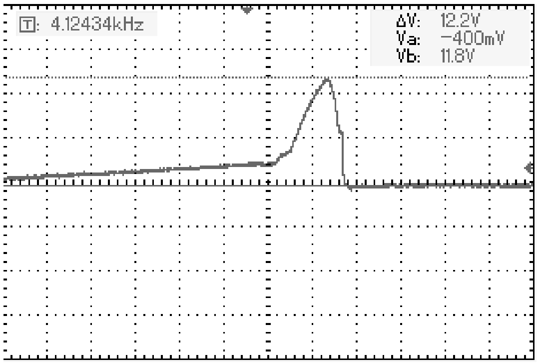

Figure 4. Peak $V_{GS} = 12.2\ V$

$(5\ V/DIV)$
$(5\ \mu s/DIV)$

Now dividing information in Figure 4 into 3 parts $(A, B$ and $C)$ and showing in Figure 5 below:

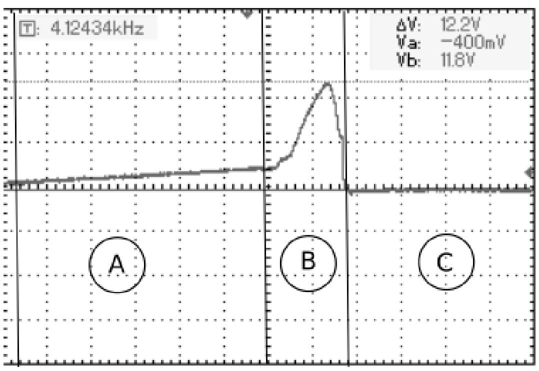

Figure 5. Peak $V_{GS} = 12.2\ V$

$(5\ V/DIV)$
$(5\ \mu s/DIV)$

Analyzing A region: In region A (Figure 5), power transistor in Q_1 (Figure 1) and transistor Q_2 is off. Q_2 transistor is off because there are no current in sensor drain I_{sensor} and output value V_O is below threshold voltage reference (negative feedback disabled). Q_1 transistor is off because positive feedback is disable by voltage applied in the gate is below $(V_{th} \approx 4\ V)$, where, V_{th} is threshold voltage of the power transistor Q_1. Static protection is enabled only if some atypical behavior (malfunction) occurs. Only current source I_{sink} is driving the gate of Q_1. Region A is also known as dead- time, where negative feedback is off and there are no magnetic energy into the transformer core. Decreasing dead-time, we can increase performance increasing output power. Adjusting I_{sink} we could improve swicthing for this application. We can also estimate capacitance including gate and circuitry capacitance using only result obtained from measurements in Figure 4.

$$\boxed{I_{sink} = C\frac{dV_{GS}}{dt}} \tag{3.0.1}$$

$$I_{sink} = C\frac{\Delta V_{GS}}{\Delta t} \tag{3.0.2}$$

Given values:

$$I_{sink} \approx 4.54\ mA$$

$$\Delta V_{GS} \approx 4\ V$$

$$\Delta t \approx 30\ \mu s$$

$$\therefore$$

$$C\ \approx\ 34\ nF$$

Where C is the total capacitance of gate and control circuit.

Analyzing B region: When voltage in V_{GS} reaches threshold voltage (V_{th}), power transistor begins to inject current in primary coil of the transformer T_1. Positive feedback is active at this moment and it forces voltage slope to get higher until it reaches a $12V$ maximum voltage. Clamper guarantees that the maximum voltage in V_{GS} not exceed $12\ V$. At this time I_D (primary coil current) is linear as shown in Figure 3

Analyzing C region: When voltage through R_{sensor} in Figure 1 exceeds $\approx 1.4\ Volts$ transistor Q_2 turns on forcing voltage gate V_{GS} close to $0\ Volt$. Control circuit and negative feedback force Q_2 base being polarized until all magnetic energy stored in transformer core T_1 beeing transfered to secondary circuitry. When all magnetic energy is trasnfered and/or negative feedback is open all process begins a new cycle.

4. Removing audible noise

Burst frequency and a high flux peak are the main issue for audible noises.

I had found a good article [2] explaining a good method to reduce this problem. To solve this problem, I had put a RC low pass-filter in voltage reference in secondary side. Decreasing burst switching frequency and its amplitude it is a good way to decrease or even eliminate audio noise when no load is present in the output voltage.

[2] Audible Noise Reduction Techniques for FPS Applications

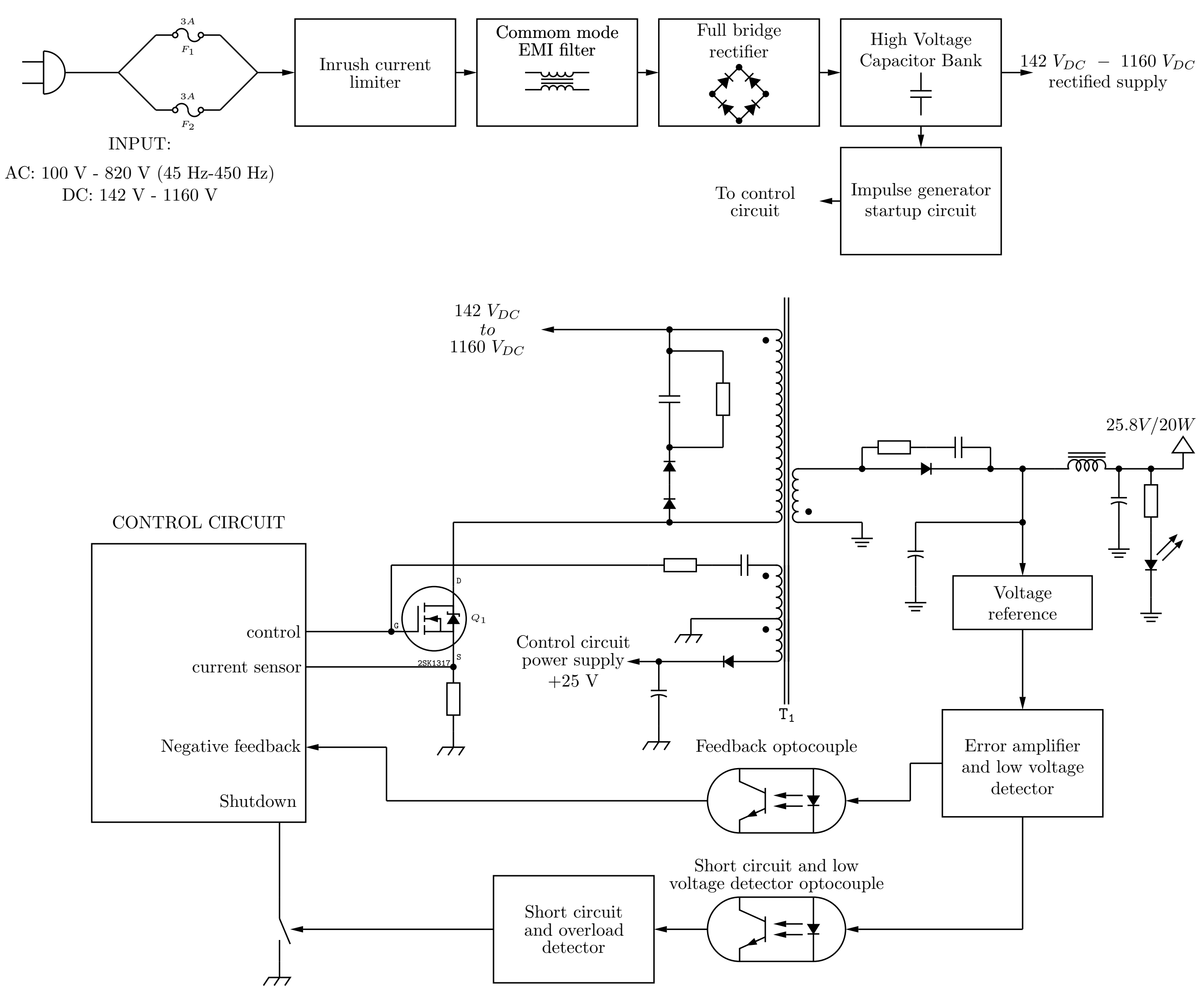

Figure 6. My Tesla-SMPS basic block

5. HV-SMPS Characteristics

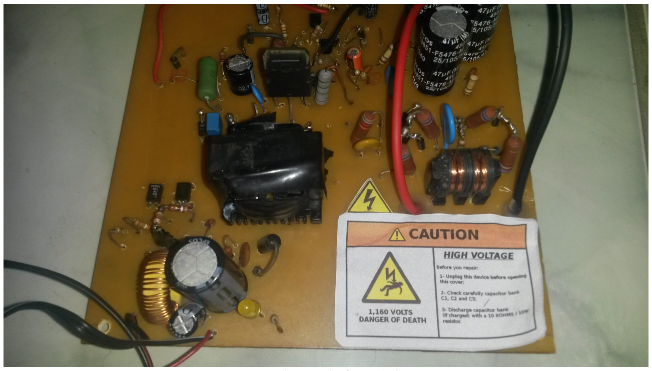

Figure 7. My sencond and final improved prototype

Table 2. Tesla-SMPS Main Characteristics (max. ratings)

Input Voltage:	$AC\ 100 \sim 820\ Volts$ $DC\ 142 \sim 1,160\ Volts$
Output Voltage:	$DC\ 25.8\ Volts\ (Insulated)$
Input power (max):	$34.3\ W/46\ Va$
Output power (max):	$20\ W$
Frequency:	$0\ Hz\ or\ 45\ Hz \sim 450\ Hz$
Eficiency: (stimated)	0.78 @ $180\ V_{DC}/127\ V_{AC}$ 0.70 @ $500\ V_{DC}/350\ V_{AC}$ 0.65 @ $1,160\ V_{DC}/820\ V_{AC}$
THD:	0.75
Insulation:	$2,600\ V_{RMS}$
Inrush current:	$42.6\ A$ @ $1,160\ V_{DC}$
I^2t **value** @ $1,160\ V_{DC}$**:**	$0.38\ A^2 s$
Primary coil value:	$1.1\ mH$
Primary coil peak current:	$933\ mA$

6. Conclusions

I've made some test with my first automation prototype and other embedded computer. This was quite versatile. So we are able to supply any low power embedded devices to a wide voltage range (industrial/home application). Some photos below and real time measurements.

About the author

Fábio Pereira da Silva (Rio de Janeiro, Brazil 1981)
is a self-taught Engineer, Self-taught Physicist, Programmer, Hardware designer, Hobbyist, Linux Lover, Cryto Lover and Libertarian.
I believe voluntarianism and tecnology to increase our acknowledgement and build a bettter world without any government centralization.
For details, please contact me at fabioegel@gmail.com

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Any question e-mail me at: fabioegel@gmail.com