

Wide Voltage Range Tesla SMPS

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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 providing control, oscillation, positive and negative feedback, short-circuit protection, overload and under-voltage protection.

Keywords

High voltage — SMPS — Tesla SMPS — Wide Range Power Supply — Embedded Power Devices

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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 circuitry. Analysing Flyback topology in Figure 1.

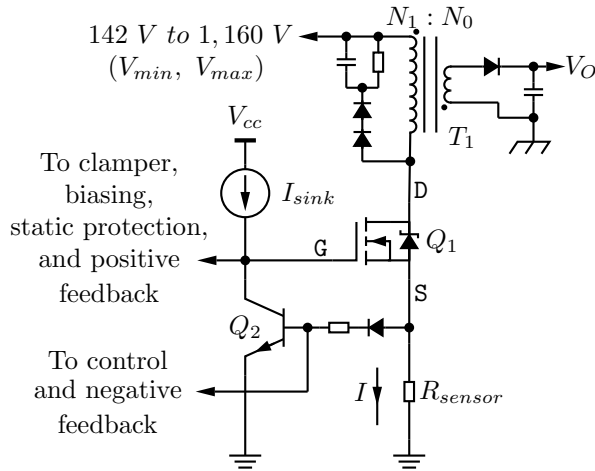


Figure 1. Flyback topology in my Tesla SMPS

Let:

- I \Rightarrow the maximum current peak
- V_{min} \Rightarrow the minimum voltage of the input circuit
- V_{max} \Rightarrow the maximum voltage of the input circuit
- V_1 \Rightarrow input voltage

V_0 \Rightarrow desired output voltage

N_0 \Rightarrow number of turn in secondary coil

N_1 \Rightarrow number of turn in primary coil

P_{min} \Rightarrow minimum output power

P_{max} \Rightarrow maximum output power

T \Rightarrow time period of switching

T_{on} \Rightarrow time period on

T_{off} \Rightarrow time period off

D \Rightarrow duty cycle

L \Rightarrow inductance of the primary coil

η \Rightarrow estimated power efficiency

From Faraday's Law¹ we get:

$$LI = V_1 T_{on} \quad (2.0.1)$$

From Law of Conservation of Energy² we get:

$$V_1 T_{on} = V_r T_{off} \quad (2.0.2)$$

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

$$V_r = V_0 \frac{N_1}{N_0} \quad (2.0.3)$$

Replacing Equation 2.0.3 into Equation 2.0.2 we get:

$$\frac{T_{on}}{T_{off}} = \frac{V_0}{V_1} \times \frac{N_1}{N_0} \quad (2.0.4)$$

and

$$D = \frac{1}{1 + \frac{V_1 N_0}{V_0 N_1}} \quad (2.0.5)$$

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

$$P = \frac{1}{T} \times \frac{LI^2}{2} \quad (2.0.6)$$

Replacing Equation 2.0.1 into Equation 2.0.6 we get:

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

We know that:

$$T_{on} = DT \quad (2.0.8)$$

Replacing Equation 2.0.8 into Equation 2.0.7 we get:

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

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:

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

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

$$I = 933 \text{ mA}$$

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

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

$$V_0 = 25.8 \text{ Volts}$$

$$N_0 = 4 \text{ Turns}$$

$$N_1 = 30 \text{ Turns}$$

$$\eta = 0.65$$

Replacing into Equation 2.0.10

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

So

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

And

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

So

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

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:

$$T = \frac{LI}{DV_1} \quad (2.1.1)$$

\therefore

$$f = \frac{DV_1}{LI} \quad (2.1.2)$$

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

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

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

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

and

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

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

Calculating V_{Dmax} and V_{Dmin}

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:

$$V_{DS} = V_r + V_{DC} \quad (2.2.1)$$

where:

$$V_{DS} = V_0 \frac{N_1}{N_0} + V_{DC} \quad (2.2.2)$$

Replacing Equation 2.2.2 with given values we get:

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

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

and

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

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

Choosing the transistor

I had found a good transistor 2SK1317 from Renesas website¹ 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 efficiency of my Tesla 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 microcontrollers 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.

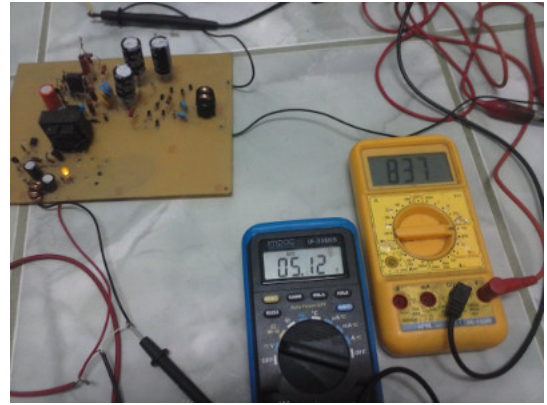


Figure 2. My first prototype testing before improvements:

Input voltage : 837 V_{AC} @ 60 Hz

Output voltage : 5.12 V_{DC}/6 W

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

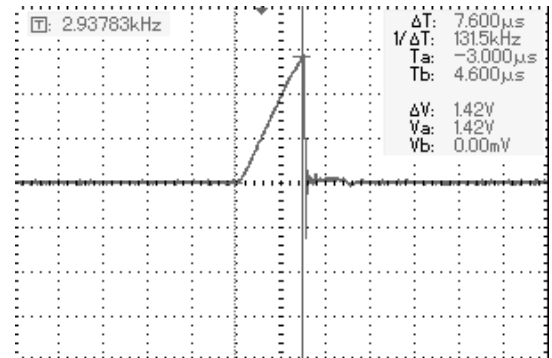


Figure 3. Peak current $I = 946 \text{ mA}$
with $R_{\text{sensor}} = 1.5 \Omega$

(500 mV/DIV)
(5 μs/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.

¹Renesas 2SK1317 datasheet

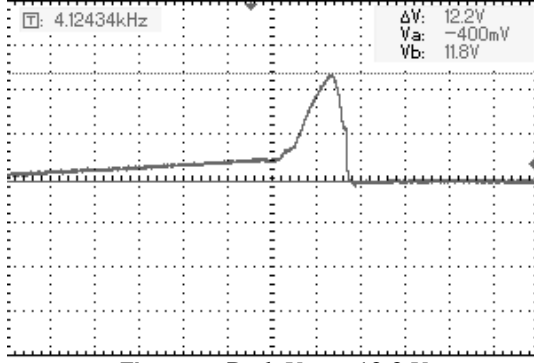


Figure 4. Peak $V_{GS} = 12.2\text{ V}$

(5 V/DIV)
(5 μs/DIV)

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

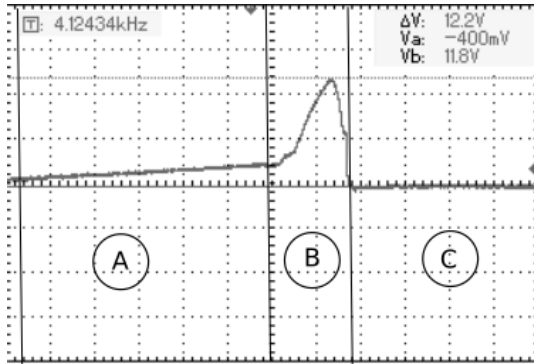


Figure 5. Peak $V_{GS} = 12.2\text{ V}$

(5 V/DIV)
(5 μs/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 disabled by voltage applied in the gate is below ($V_{th} \approx 4\text{ V}$), 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 switching for this application. We can also estimate capacitance including gate and circuitry capacitance using only result obtained from measurements in Figure 4.

$$I_{sink} = C \frac{dV_{GS}}{dt} \quad (3.0.1)$$

$$I_{sink} = C \frac{\Delta V_{GS}}{\Delta t} \quad (3.0.2)$$

Given values:

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

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

$$\Delta t \approx 30\text{ μs}$$

∴

$$C \approx 34\text{ nF}$$

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 $\approx 1.4\text{ Volts}$ 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 being transferred to secondary circuitry. When all magnetic energy is transferred 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

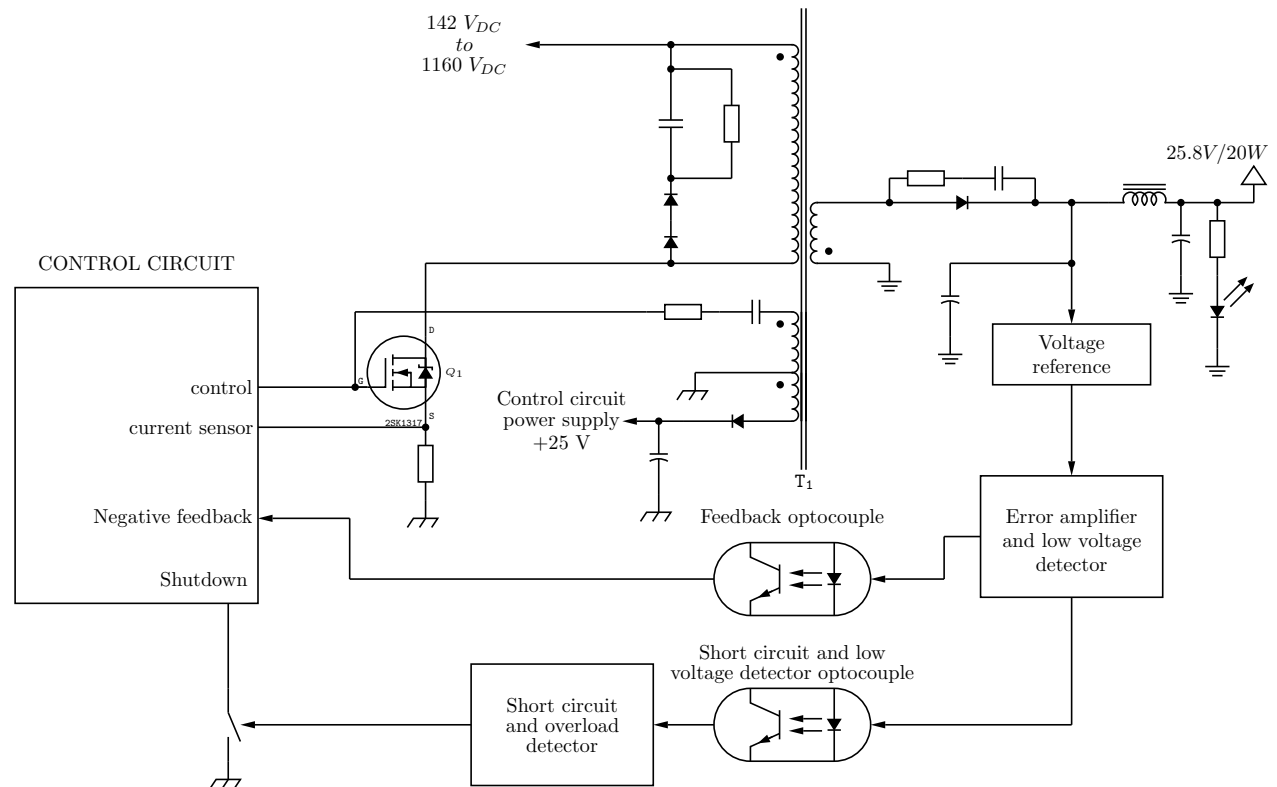
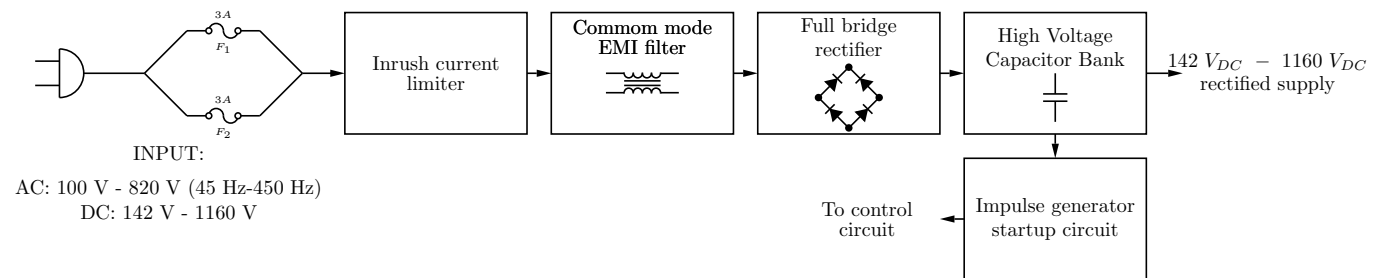


Figure 6. My Tesla-SMPS basic block

5. HV-SMPS Characteristics



Figure 7. My sencond and final improved prototype

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

Input Voltage:	AC 100 ~ 820 Volts DC 142 ~ 1,160 Volts
Output Voltage:	DC 25.8 Volts (<i>Insulated</i>)
Input power (max):	34.3 W / 46 Va
Output power (max):	20 W
Frequency:	0 Hz or 45 Hz ~ 450 Hz
Efficiency: (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}
I²t 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 and real time measurements.



Figure 8. My embedded working @ 1032V_{dc} to 25.60 V_{dc}

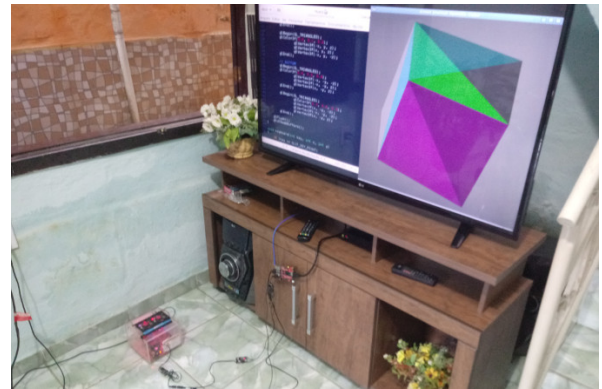


Figure 9. Linux embedded using my Tesla SMPS

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, Crypto Lover and Libertarian. I believe voluntarianism and tecnology to increase our acknowledgement and build a better world without any government centralization. For details, please contact me at fabioegel@gmail.com



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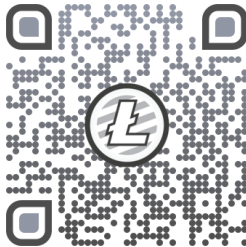
More details and DIY PCB project are available at my
github repository: <https://github.com/devfabiosilva/myTeslaSMPS>

Nano (XRB)



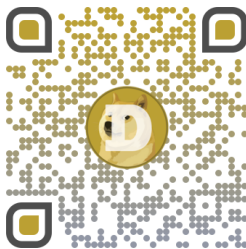
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Litecoin (LTC)



LRjEiKadFzPCoGorWvSVUnWPsFyPZGt97f

Dogecoin (DOGE)



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