DC Voltage Regulator for small wind turbine systems tied to the Grid

Introduction

This document presents a project of a DC bus voltage regulator, designed to be used in small wind turbine systems, tied to the electrical grid, precisely with Piggot's turbine of 1.80 m and 2.40 m which has nominal power of 350 W and 700 W respectively.

Problem Description

Small wind systems tied to the electrical grid are typically structured as showed in fig 1.

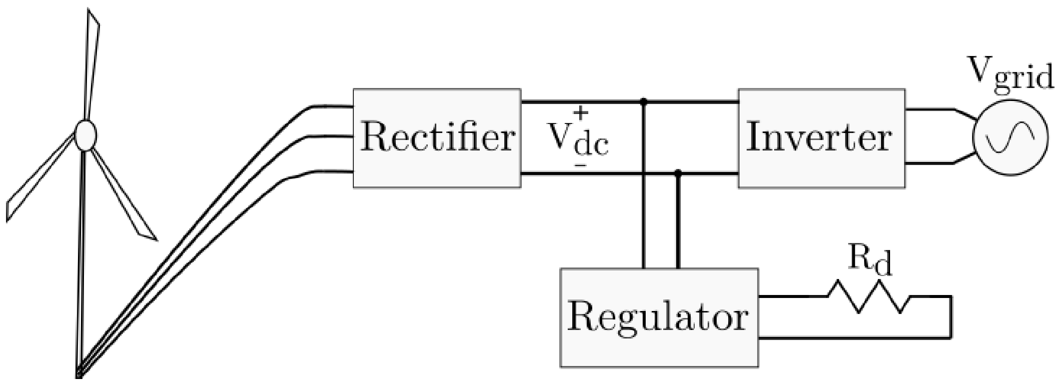


Figure 1: Small wind turbine system

The inverter start transferring energy to the grid whenever the DC voltage (V_{dc}) generated by the wind turbine is higher than a minimum level, in this present work, the inverter used will be Mastervolt's Windmaster, which minimum level is at 60 V. The startup process of the inverter may take up to 30 seconds, and while the wind turbine turns without sending the energy to the grid, its voltage rises proportionally with the wind speed as showed in figure 2.

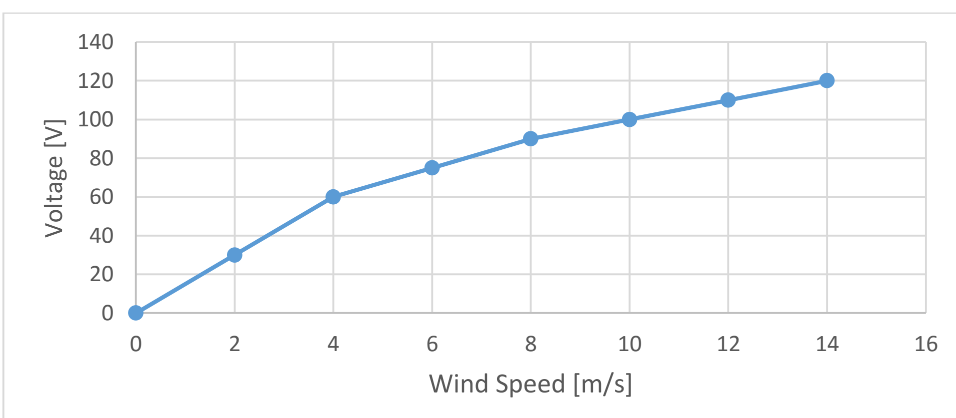


Figure 2: Open Circuit Voltage versus Wind Speed

During these 30 seconds, or any other occasion that the inverter stops working, it's important to regulate the DC voltage in order to not damage the electronic equipment, as the inverter or the rectifier.

The most common technique is connecting a resistance to the DC branch through a power switch, which is commanded when the voltage rises over a certain level, in figure 1 it is showed as the Regulator box. Different techniques can be used to control the DC voltage.

System Electrical Limits

The regulator is designed to be used with two different wind turbines as showed in the table 1.

	Piggott's 1,8 m	Piggott's 2,4 m
Nominal Power [W]	350	700
Generator Nominal Voltage [V]	48	48
Open Circuit Voltage @ 10 m/s [V]	100	100

Table 1: Wind Turbines Characteristics

A different resistance is designed with each turbine; their parameters are calculated as following.

Resistance rated power (P_R): Greater than 150% of the system rated power.

Electric resistance (R_d): The resistance must drain 100% of the system power in the desired regulated voltage. Choosing 80 V to be the desired regulated DC voltage (V_{dc}) in both systems, the electrical resistance value must be lower than

1.8m Turbine $$R_{180} = \frac{V_{dcD}^2}{P_N} = \frac{80^2}{350} = 18{,}3\Omega$$

2.4m Turbine $$R_{240} = \frac{V^2}{P_N} = \frac{80^2}{700} = 9\Omega$$

It has been chosen a value of 6 Ω to ensure a safety margin. With the resistances defined, it's possible to calculate the maximum DC current that will flow through the circuit.

1.8m Turbine $$Imax_{180} = \sqrt{\frac{P_N}{R_d}} = \sqrt{\frac{350}{6}} = 7{,}6\ A$$

2.4m Turbine $$Imax_{240} = \sqrt{\frac{P_N}{R_d}} = \sqrt{\frac{700}{6}} = 10{,}8\ A$$

Hysteresis Control

A hysteresis control strategy consists in keeping the measured value inside two hysteresis bands pre-defined. In figure 3 a general schematic of the system is showed.

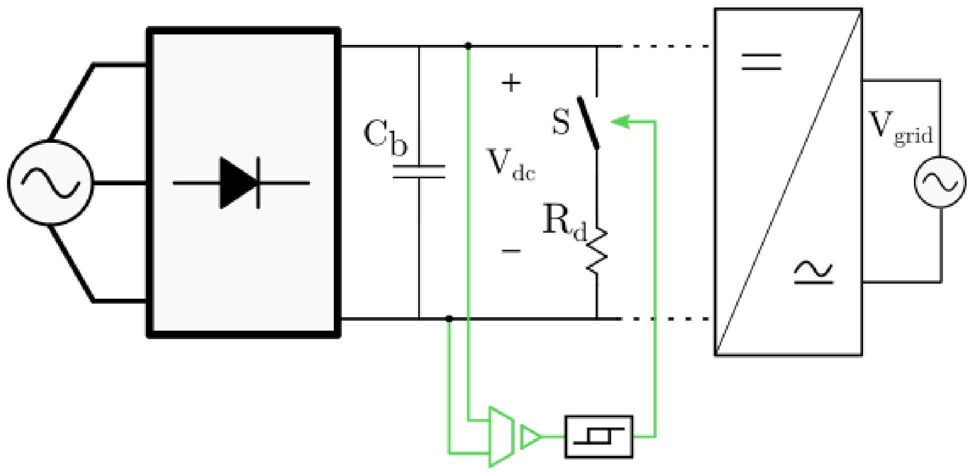


Figure 3: General Schematic

Opening an inductive circuit may cause voltage peaks, that might be harmful to the power switch. In order to avoid this, it is important to insert a capacitor (C_b) in the DC bus, this capacitance will define the switching frequency.

System Model for Control Design

For the system modelling will be considered that the DC bus is open, no energy flows through when the power switch is open, that means that the generator will provide the maximum voltage possible which is the worst case scenario for the semiconductors.

Considering the wind speed at 10 m/s, the maximum power the turbine can provide is 700 W. While the resistance is connected, the maximum current that can flow is given by

$$I_R = \sqrt{\frac{P}{R}} = \sqrt{\frac{700}{6}} = 10.8\ A$$

As the generator has a high inductive characteristic, is possible to consider it together with the diode bridge as a DC current source with a maximum value of 10.8 A. So the circuit running with the hysteresis control would work in the two situations showed in figure 4.

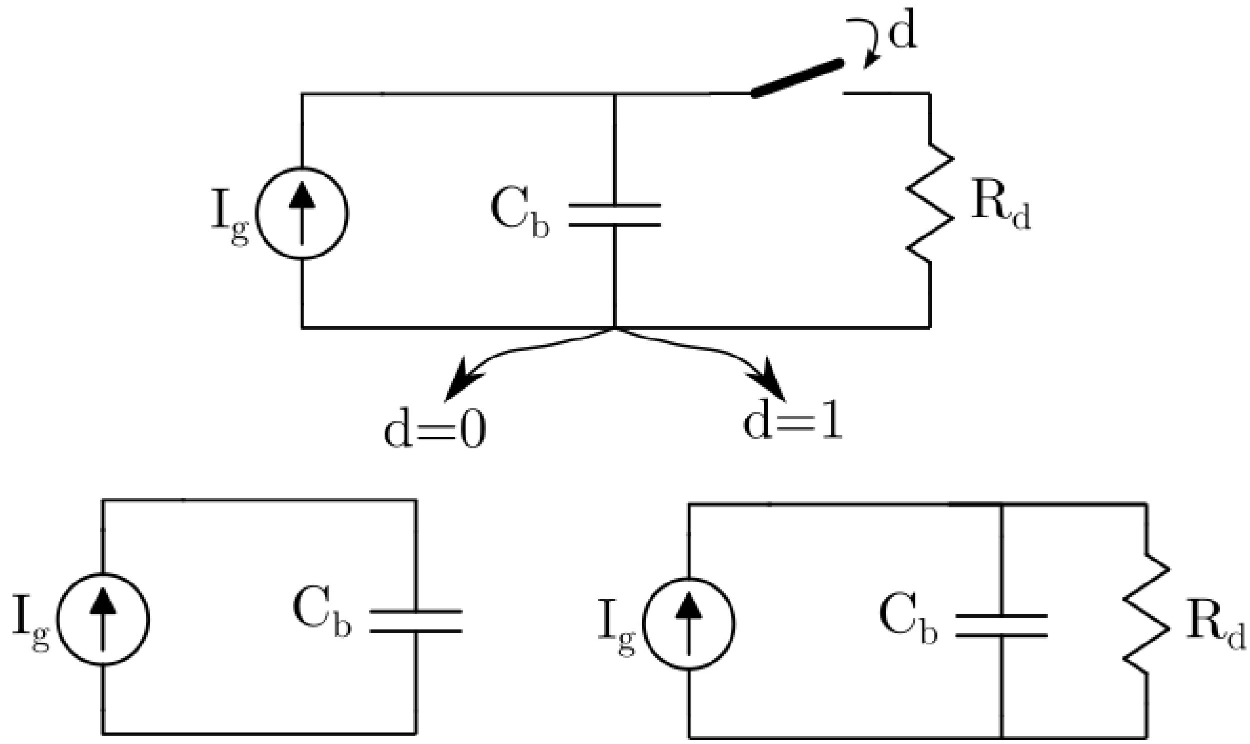


Figure 4- Generator's DC Model

The hysteresis solution, where two hysteresis limits are defined, and as soon as the voltage cross one of them, the power switch is commanded. The hysteresis controller is a non-linear strategy that will result in a variable switching frequency, that will depend on the **capacitance C_b**, the **DC current** and the difference of voltage of the low and high level **ΔV**.

The figure 4 illustrates the DC voltage expected behavior while functioning with a hysteresis controller.

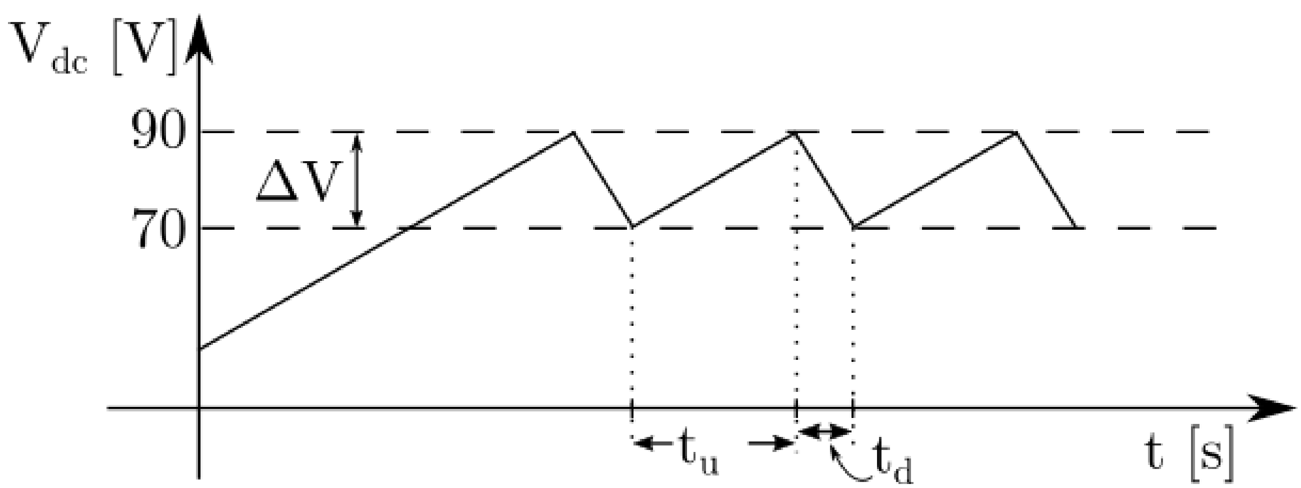


Figure 5: DC voltage regulation with hysteresis limits

The rise of the voltage that defines the time t_u happens when the power switch is open, so the voltage will rise as the current source charges the capacitor

$$I_g = C_b \frac{\partial V_c}{\partial t}$$

so the time to charge the capacitor 20V with will be

$$\boldsymbol{t}_u = C_b \frac{\boldsymbol{\Delta} V_c}{I_g} = 1.85 C_b$$

Now, considering the power switch commanded, the 90 V will be imposed in the resistor, so the voltage will drop as a RC circuit. As only 20 V will be discharged, it is possible to simplify without many errors as if the current drained by the resistor by a constant 80 V during t_d.

$$I_R = \frac{V_c}{R_d} = \frac{80}{6} = 13.33$$

so the capacitor will discharge with a current of I_R – Ig resulting in 1 A. So the time td will be

$$\boldsymbol{t}_d = C_b \frac{\boldsymbol{\Delta} V_c}{I_r - I_g} = 7.89 C_b$$

The switching frequency will be defined by

$$f_s = \frac{1}{t_u + t_d}$$

In order to minimize the commutation losses, the regulator will be designed to work with a low switching frequency. For an operation bellow 500 Hz, a capacitance of 200 uF should be added.

Simulation Results

To ensure the operation of the strategy simulations were made with the software PSIM. Figure 7 shows the results of the voltage in the DC bus, when the generator with the power switch operating with a frequency lower than 500 Hz.

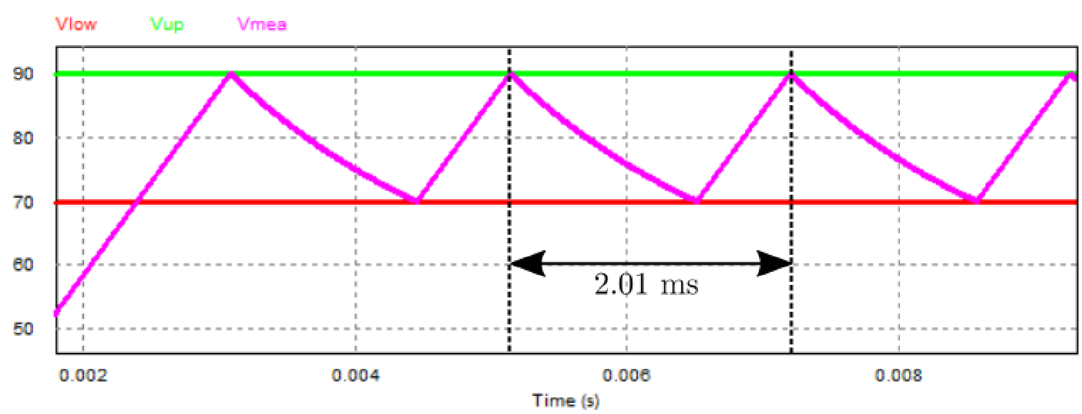


Figure 6- DC Voltage operating in 700W

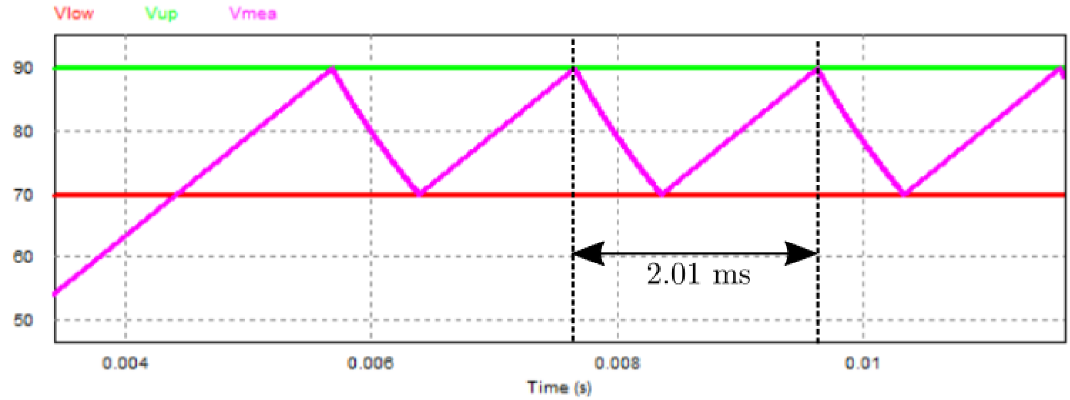
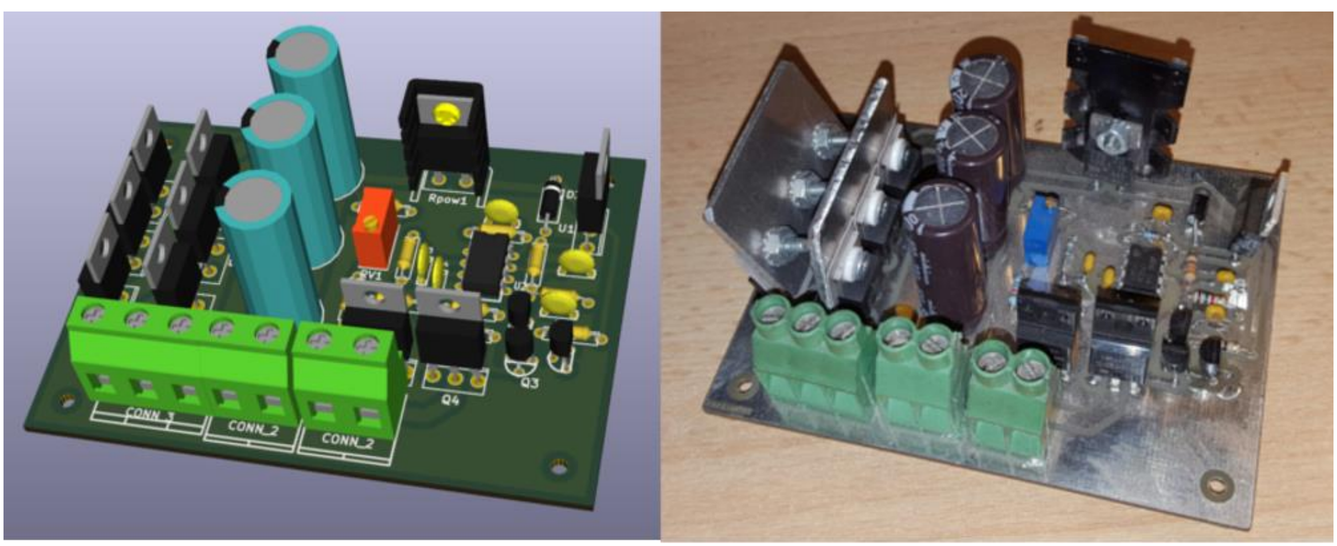


Figure 7- DC Voltage operating in 400W

Prototype

A hysteresis circuit can be easily done with a comparator integrated circuit. The LM311 was selected for it. A power supply in 15V was done with a Zener diode and a resistance, and a gate drive circuit for providing enough current to drive the MOSFETs as well. Two Infineon IRFI4227 were designed as power switches due its low ON resistance of 21 mΩ. The hole schematic is presented in the Annex 1.

A Layout was designed using the software KiCAD. The prototype includes a diode bridge, the DC capacitors, the hysteresis circuit and gate drive circuits for the MOSFETs.



Practical results

The prototype was tested with a Piggott's 2,40 m generator that was driven with a motor which was driven by an inverter. Figure 8 shows the DC voltage when the generator was processing 400 W.

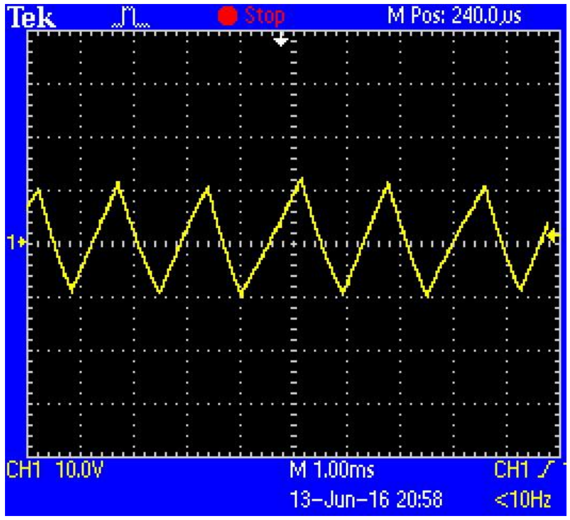


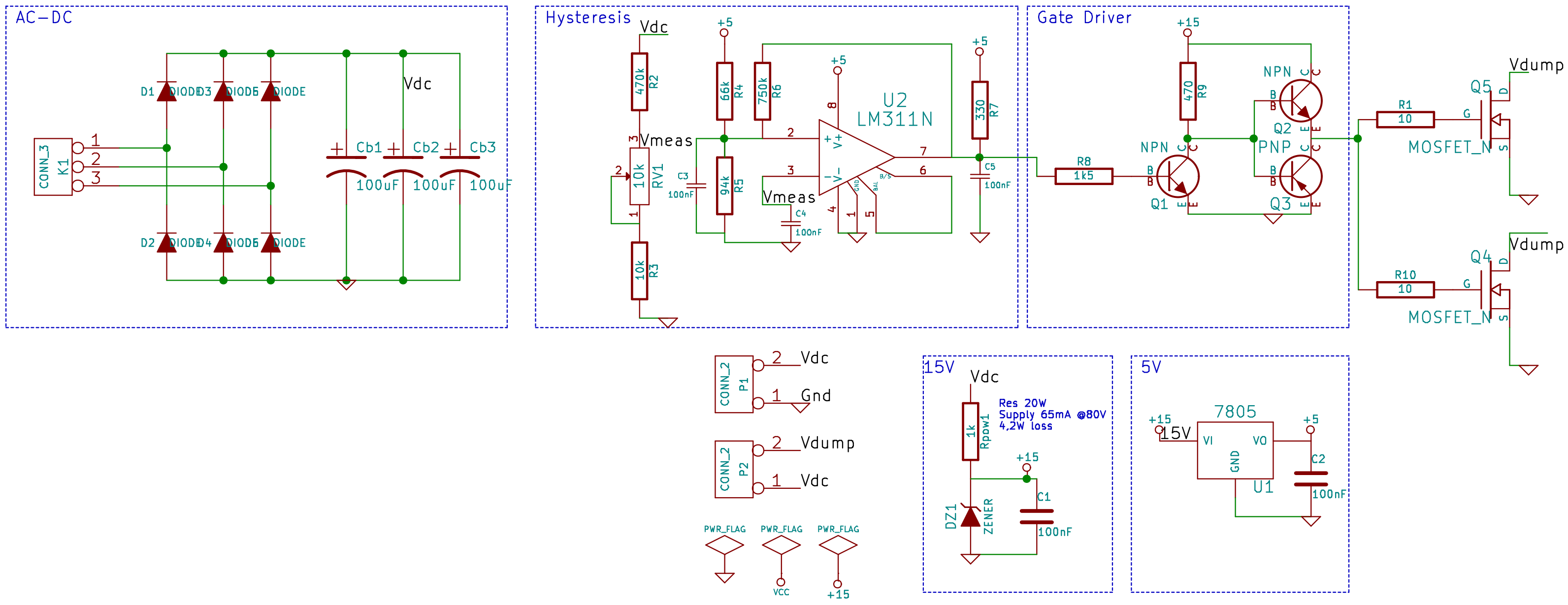
Figure 8- Experimental result - DC Voltage in 400 W

The switching frequency corresponds to the simulation results, with an average period of 2 ms. But due many non-idealities not considered in the model, the frequency is variable.

Conclusion

This work presents a dump load controller for small wind turbine systems, which was designed to work with Hugh Piggott's 1,80 m and 2,40 m with 48 V nominal voltage generator. The proposed controller utilizes a hysteresis control solution that is implemented analogically that runs within a maximum switching frequency of 500 Hz.

Also a model of the 48 V generator is presented. Simulations with the model and the proposed hysteresis solution are showed and the practical results proves that the model represents quite well the real system.



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