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MANUSCRIPT TRACK: Smart Grids

SWITCHING POWER SUPPLIES IN DC GRIDS: THE SMART CURRENT LIMITER

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Abstract:
The Smart Current Limiter is a switching DC to DC converter that provides a digitally pre-set input current control for inrush limiting and power management. Being able to digitally adjust the current level in combination with external feedback can be used for control systems like temperature control in high power DC appliances.
Traditionally inrush current limiting is done using a passive resistance whose resistance changes depending on the current level. Bypassing this inrush limiting resister with a Mosfet improves efficiency and controllability, but footprint and losses remain large.
A switched current mode controlled inrush limiter can limit inrush currents and even control the amount of current passing to the application. This enables power management and inrush current limitation in a single device.
To reduce footprint and costs a balance between losses and cost-price on one side and electromagnetic interference on the other side is sought and an optimum switching frequency is chosen. To reduce cost and copper usage, switching happens on a high frequency of 300kHz. This increases the switching losses but greatly reduces the inductor size and cost compared to switching supplies running on lower frequencies. Additional filter circuits like snubbers are necessary to keep the control signals and therefore the output current stable.

Keywords:
DCgrid, Limiter,Inrush, Short Circuit Protection

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I. INTRODUCTION

An AC voltage of 230V is currently used for all household appliances in Europe. Because of the change of energy production from coal fired steam driven AC generators towards renewable energy sources such as solar power, the application of a DC grid is becoming a natural choice for distribution. Power management is implemented using power electronics and the local production is easily connected to a DC grid. Applying a DC-grid for households, appliances that directly connect to a DC grid are required. The Dutch NPR9090 [1] is a guideline on how DC can be implemented. The NPR9090 outlines how a DC-Grid with a voltage level of 350VDC should implemented. But how to turn-on and off an oven, infrared heating panel or other high power appliance? These appliances have a low input impedance and therefore show a large inrush current.

To prevent this inrush current a non-linear series resistance is often placed in series with the application, whose resistance reduces for lower currents [2]. In that way inrush currents in AC appliance are limited. In DC appliances, the inrush current is a higher, as there is no AC impedance that limits the inrush current. Therefor active current limiting by using a controlled MOSFET as series resistance is applied. Since the input voltage that must be withstand and the final load current can be large, this MOSFET is bulky and requires a large footprint. For this reason a switched mode power supply [SMPS] current limiter is developed, based on the current controller for DC appliances [3]
The current limiter is introduced in section II, where the basic structure is shown.
In Section III the current limiter is outlined and the difference between a series resistance application and a switched mode current limiter is explained. In section IV the impact of the switching frequency and choice of inductor is discussed. The filtering of

current measurements for the control are outlined in section V and in section VI the current limiter is extended using a microcontroller to implement power management.

II. Current Limiter

The current limiter is a DC to DC switching converter that can limit the current to a preset value. This means that limiting the current to a resistive load will provide a constant current at the output. If an AC resistive load is used which is meant for 230VAC, the current limiter will give an output voltage of 230VDC if set for the same amount of power. A block diagram of the current limiter is shown in Fig. 1. The entire schematic can be found in [2]

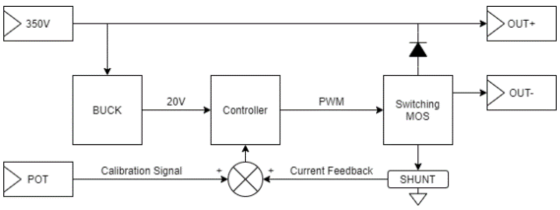

Fig. 1: Block schematic of the current limiter

From the 350V input voltage a lower 20V is created using a step down converter [4], to power all the electronics. The output stage has a buck-topology using a switching MOSFET and a diode. The output current is measured across a shunt, added to the calibration signal and fed to the controller IC. The controller is the UC3842 [5]. When the sum of the feedback signal and the calibration signal rises above an internal threshold voltage of 5V, the output gets turned off. This happens based on an internal clock of which the oscillator frequency is around 300kHz. This process is also shown in Fig. 2

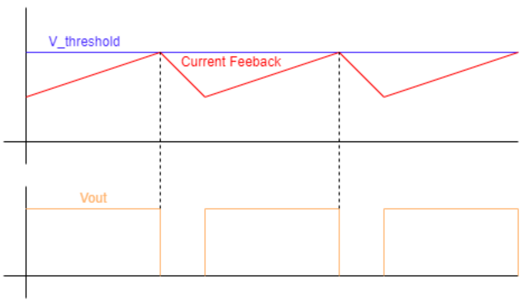

Fig. 2: Regulation of the averaged output current with peak current control. Vout controls the MOSFET and therewith the averaged output current.

III. Droop Voltage and Inrush Current

Voltage droops and inrush currents are the two typical phenomena that are present in DC grids [6]. Voltage droops on the grid occur when users are drawing energy from the grid. This means that being able to read out the DC grid voltage will give us information about the amount of power which is available on the net. These voltage droops will not be a problem with the current limiter because it already provides a constant current at the output, therefore the output level will be unaffected by changes on the DC grid as long as enough power is available to provide the desired current. Considering a DC output voltage of 230V and the standards of [1] which say the net voltage will be between 300 and 400V, this will always be the case.

The second phenomena is inrush current. When an application is turned on, all the capacitance within the circuit have to be charged. When connecting an appliance to the DC grid a large inrush current will appear. An active short circuit protection will not be able to distinguish this current peak from short circuit and will therefor trip [7]. A typical inrush current is shown in Fig. 3, where a peak current around 150A can be seen.

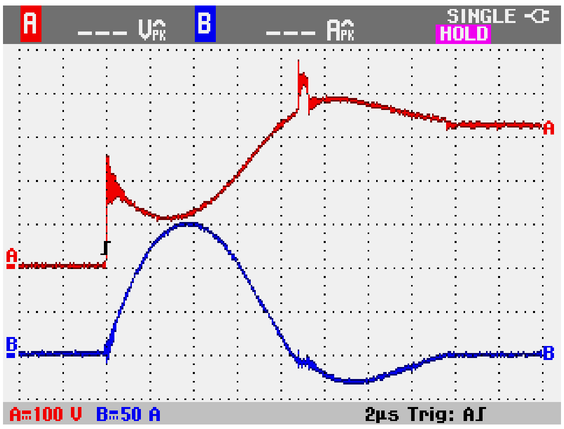

Fig. 3: Inrush of the current limiter, where signal B is the inrush current and signal A the voltage drop during inrush.

An inrush protection can be made using a wire wound resistor and a FET[18]. A wire wound resistor is placed in series on the low side and bypassed by the FET after time. A simulation model using Caspoc Simulation[8] of this is shown in Fig. 4.

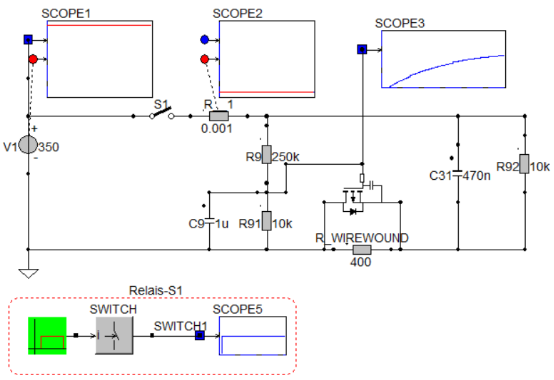

Fig. 4: Simulation of inrush protection using Caspoc Simulation [8], scope 1 shows the input voltage and current, scope 2 the inrush current and scope 3 the gate voltage controlling Rds of the MOSFET

Scope 3 in the simulation shows the voltage on the gate of the FET slowly rising, causing the wire wound resistor to be bypassed over time. This solution is cheaper and less big compared to the existing protection [9], however the FET's internal resistance will cause losses[10].

IV. SMPS CURRENT LIMITER

Instead of a linearly controlled Mosfet a SMPS current limiter as shown in Fig. 1 is applied. The average output current is regulated using a current mode control IC[5] with a high switching frequency. Increasing the switching frequency increases the switching losses but also greatly decreases the conductor size and cost. Using [11] together with a maximum current ripple of 40%, an output wattage of 3kW and output voltage of 230V, which is the case in the current limiter design, formula 2 can be derived.

$$L = \frac{E_t}{rI_o} \quad (1)$$

$$L = \frac{(V_{in} - V_{sw} - V_o)t_{on}}{rI_0} \quad (2)$$

Using (2) together with the 3kW-proof inductors as shown in [12], [13], [14] from 40 to 220kHz and [15] (shielded) from 300kHz and up, we get the graphs shown in Fig. 5 and 6.

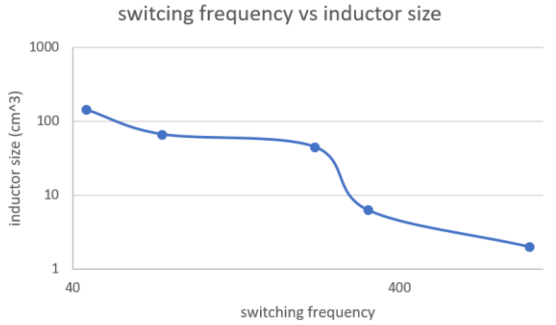

Fig. 5: Plot of the inductor size in cm^3 to the switching frequency of the current limiter.

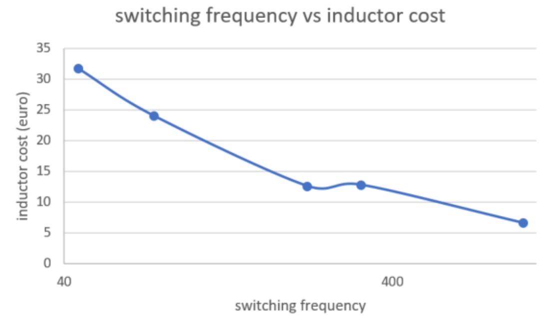

Fig. 6: Plot of the inductor cost in Euro to the switching frequency of the current limiter.

A higher switching frequency will also increase the switching losses. Using [16], an approximation of the switching losses can be made using (5).

$$P_{SW} = 2(E_{t1} + E_{t2})f_{SW} \quad (3)$$

$$P_{SW} = V_{DS}I_{DS}\left(\frac{Q_{GS2}}{I_{GS}} + \frac{Q_{GD}}{I_{GS}}\right)f_{SW} \quad (4)$$

$$P_{SW} \approx V_{in}I_{out}\left(t_r + t_{d(on)}\right)f_{SW} \quad (5)$$

The total amount of MOSFET losses consist of the switching losses, gate losses and resistive losses. However the switching losses are the biggest factor in the frequency dependent losses. The gate charge losses (4)are the biggest factor in the switching losses. Using a MOSFET with a low gate charge is essential for keeping the total losses low when using a higher switching frequency. This has been done for the current limiter running at 300kHz as shown in [9] and gives us efficiency above 90% for an output power of 800W up to 2kW+ as shown in [10].

V. FILTERING AND STABILITY

Filtering the PWM and output signals is necessary to prevent interference with the control signals. Next to using an output inductor as commonly used in the buck topology, additional snubber circuits and other first order passive filters are applied. Fig. 7 shows the internal comparison voltage of the current limiting IC when no additional filters are used, which should give a stable output voltage level.

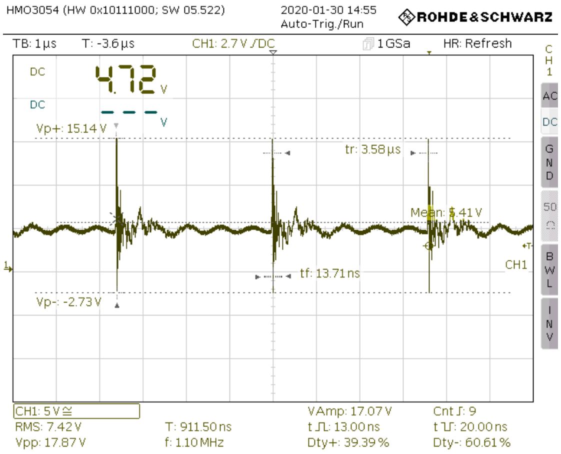

Fig. 7: Internal comparison voltage of the current limiting IC

Adding additional RC low-pass filters around the comparison signal does decrease the spike level. In Fig. 8 we can see the output signal A of the current limiter in progress. Signal B shows us the internal comparison voltage after the RC filters have been added. The spike level has been decreased from 15V to roughly 2 to 3V. The spikes match with and occur at the same moment the spikes of the output signal.

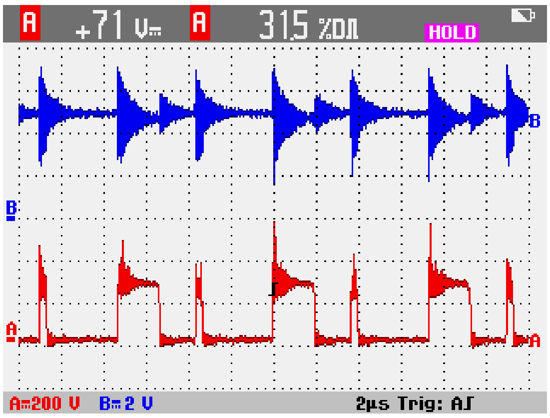

Fig. 8: Unfiltered output of the current limiter interfering with the comparison voltage. Signal A is the PWM of the current limiter, while signal B is the control signal.

Any spikes occurring on the PWM signal can simply be reduced using an RC low-pass filter as shown in Fig. 9 and 10.

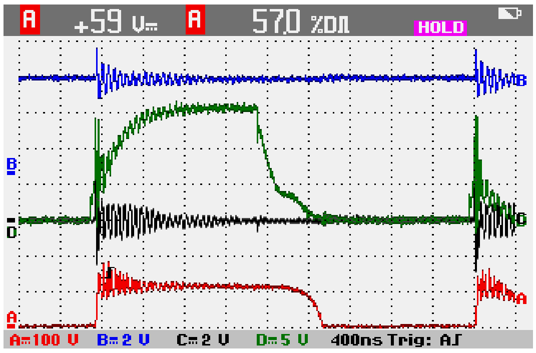

Fig. 9: Signal D shows a large spike during turn-on, before adding an RC low-pass filter

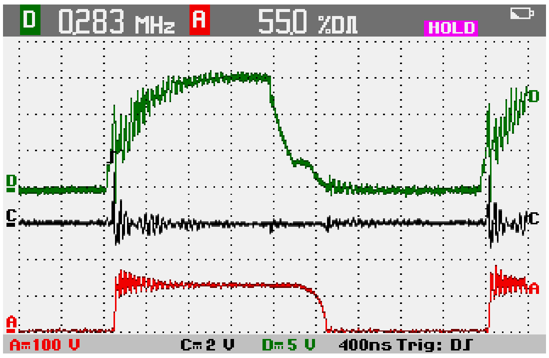

Fig. 10: Signal D shows the filtered signal. Adding an RC low-pass filter, the peak on signal D is clearly reduced

To reduce the ringing spikes on the unfiltered output voltage a snubber can be implemented into the design. In order to design a snubber circuit capacitance and inductance of the diode and MOSFET must be known. These values are determined by the MOSFET, diode and by the traces in the PCB. A way to find these values and design a snubber filter is shown in [17]. The output ringing is shown in Fig. 11. This has a ringing frequency of 40MHz.

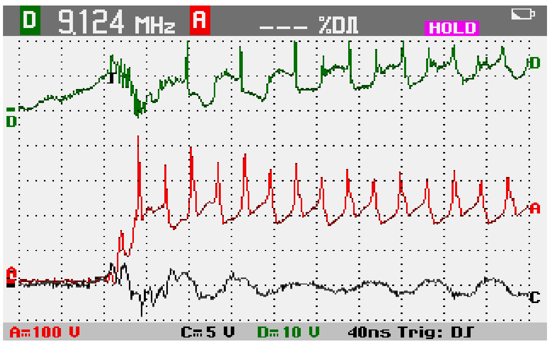

Fig. 11: Ringing measured across the MOSFET to calculate the snubber circuit parameters from the ringing frequency.

According to [17] the required capacitor value for the snubber is found when the ringing frequency is reduced by a factor √2, which would give a frequency around 28MHz. A capacitor of 10pF is placed parallel to the diode and gives a signal which has the desired ringing frequency of 28MHz.

This means that the inductance can be calculated using formula 6.

$$f_{turn-on} = \frac{1}{2\pi\sqrt{L_S C_O}} \rightarrow L_s = 1.58\mu H \qquad (6)$$

A resistor equal to the capacitors impedance at the ringing frequency should be used, which would be 0.4kΩ.

VI. THE SMART CURRENT LIMITER

A microcontroller is implemented into the current limiter, of which the block diagram can be seen in Fig. 12.

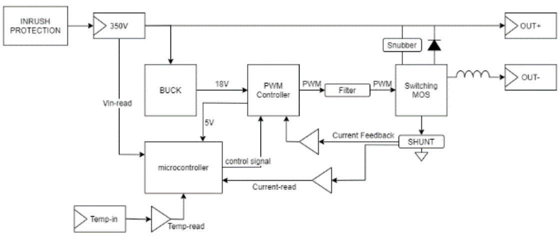

Fig. 12: Block diagram of the smart current limiter

The smart current limiter uses an Arduino Nano which has an ATMega328p microcontroller in it.

The potentiometer giving a calibration signal has been removed from the current limiter. The implemented microcontroller gives the following options:

- The comparison level of the current limiter can be adjusted, therefor the current level can be digitally set.
- The input voltage can be read out, giving information about the amount of power which is available on the grid.
- The output current can be read.
- A thermocouple or other external input can be connected to the microcontroller.

Combining the above mentioned options, gives the possibility of providing constant current to any device, reducing the amount of power used when there is less available and implementing maximum temperature control or other control systems.

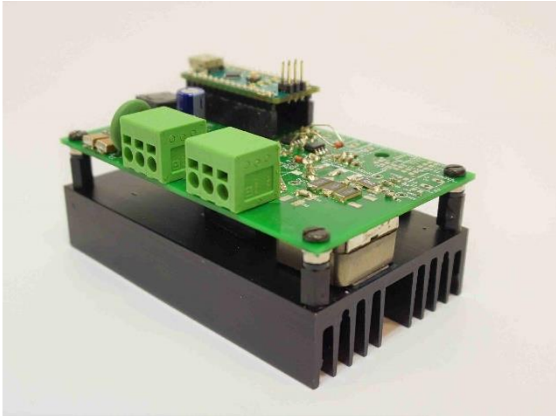

Fig 13: Realization of the smart current limiter

VII. RESULTS AND DISCUSSION

The smart current limiter is a power supply that can be used for inrush current limitation and power management. The current limiter can provide a constant current at the output, which can be digitally set. Simply implementing a voltage feedback instead of a current feedback can provide a constant output voltage, meaning grid voltage droop at the input can be handled. These voltage droops on the grid can actually be read out and used for power management [16].

Inrush is still a big problem in DC grids, linear protection circuits are available. However inrush protection based on a SMPs allows smaller and more efficient inrush protection and can be implemented with a small footprint.

To keep SMPS small and cost efficient, higher switching frequencies are essential. This will keep the inductor small and cheap. In order to do this it is important to use switching Mosfets with as low as possible gate charge. Lower gate charge losses keep the switching losses lower an therewith higher efficiency and therefore less heat production.

VIII. CONCLUSION

Inrush currents are a typical phenomenon in DC grids that exists, because there is no limiting AC impedance. Current limiters in the form of series resistance to limit the inrush current have a large footprint for the current limiting resistor. The on state resistance of a Mosfet controlled by the gate voltage is used in commercial appliances, but requires an over dimensioned Mosfet capable of withstanding the thermal impact during inrush. A switched mode power supply current limiter is more efficient compared to the series resistance and has smaller footprint that the series resistance current limiter. Experimental results confirm the simulation results in controlling the inrush current.

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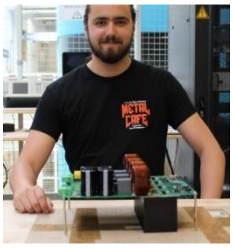
Author Biographical Statements



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