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Inrush current limiting circuit

15 FIELD OF THE INVENTION

The present invention relates to an inrush current limiter circuit for a rectifier, a rectifier, and a method for limiting an inrush current of a rectifier flowing between a rectifying part of the rectifier and a filter capacitance, and a use of the inrush current limiting circuit.

20 BACKGROUND

Rectifiers may be exposed to voltage steps that may for example occur when the rectifier is switched on or at short outages. In case of voltage steps at the input of a capacitive filtered circuit, the discharged DC bus capacitors present a low impedance across the input since the ESR (equivalent series resistance) of an electrolytic capacitor varies strongly with
25 capacitor value and supplier, ranging from a few ohms to tens of milliohms. A large input voltage step from a low impedance voltage source such as a DC battery causes a high current spike, leading to a range of problems, starting from unnecessary aging of the capacitors, up to tripping of the input fuse or permanent damage of components.

30 SUMMARY

An objective of the invention may be to provide an improved rectifier with an effective inrush current limiting circuit.

The problem is solved by the subject-matter of the independent claims. Embodiments are
35 provided by the dependent claims, the following description and the accompanying figures.

The described embodiments similarly pertain to the inrush current limiter circuit for a rectifier, the rectifier, the method for limiting an inrush current of a rectifier flowing between a rectifying part of the rectifier and a filter capacitance and the use of the inrush current limiter
40 circuit. Synergetic effects may arise from different combinations of the embodiments although they might not be described in detail.

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Further on, it shall be noted that all embodiments of the present invention concerning a method, might be carried out with the order of the steps as described, nevertheless this has not to be the only and essential order of the steps of the method. The herein presented
5 methods can be carried out with another order of the disclosed steps without departing from the respective method embodiment, unless explicitly mentioned to the contrary hereinafter.

Technical terms are used by their common sense. If a specific meaning is conveyed to certain terms, definitions of terms will be given in the following in the context of which the
10 terms are used.

According to a first aspect, an inrush current limiter circuit for a rectifier is provided, wherein the inrush current limiter circuit provides a flow of a current between a rectifying part of the rectifier and a filter capacitance. The inrush current limiter circuit comprises a power stage,
15 wherein the power stage comprises a power stage resistor (108) and a power stage transistor parallel to the power stage resistor. The power stage resistor is configured to conduct an amount of the current in dependence on the state of the power stage transistor. The power stage transistor is configured to conduct an amount of the current in dependence on a charging of a gate capacitance of the power stage transistor.

20 The term "inrush current" designates the current that occurs when the rectifier is switched on, and which charges the unloaded DC filter capacitor (or in general a capacitive load). The same effect occurs at voltage jumps on the DC lines. The voltage jump may be, for example, 15 V.

25 The power stage is the main block of the inrush current limiter circuit since it comprises the components that are finally responsible for the flow of the current between the rectifying stage and the filter capacitor. The components are a resistor and a transistor such as a MOSFET or other power transistor. The resistor may be an arrangement of several
30 transistors connected in parallel to distribute the current over more than one single resistor. Since the resistor is connected in-line, it conducts the full inrush current, limited according to the characteristics of the resistor, if the transistor is switched off. If the transistor is in a state between a switch-off state and a switch-on state, the resistor conducts a part of the inrush current, and if the transistor is switched on, it conducts no or nearly no current. In other
35 words, the amount of the current flowing through the resistor and the transistor depends on

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the charging of the gate capacitance of the transistor. Of course, there may be further dependencies such as the voltage and characteristics of the resistor and the transistor.

5 The circuit allows switching the transistor in such a way that the current is flowing either through the resistors or through the transistors, and in a short transition time through both. In this way the inrush current can be limited by the resistors, and the current limitation can be removed whereby the resistors are relieved.

10 According to an embodiment, the inrush current limiter circuit further comprises a constant current source. The constant current source is configured for charging the gate capacitance of the power stage transistor.

15 The charging of the gate capacitance of the power stage transistor is performed by the constant current source. The charging may take some time such that in a first phase, the transistor is switched off so to limit the inrush current, in a second phase, the transistor is in a short transient state, where it does not conduct fully, and in a third state, the transistor is switched-on such that the current limitation can be removed whereby the resistors are relieved. Due the short transition phase, a relatively smooth re-distribution of the inrush current from the resistor to the transistor is achieved. The resistor thus fulfills its current
20 limiting scope and is released by the transistor during nominal operation.

According to an embodiment, the constant current source is configured to charge the gate capacitance power stage transistor according to a configured time constant.

25 The constant current source may comprise a transistor such as a MOSFET that is wired to resistors and/or other devices that influence the amount of current that this provided to the gate of the power stage transistor. The time constant may be changed by adjusting the values of these devices.

30 According to an embodiment, the Inrush current limiter circuit further comprises a re-trigger circuit. The re-trigger circuit is configured to detect a DC bus voltage jump, and to turn the transistor off if it has detected that there has been a DC bus voltage jump.

35 This may be accomplished by pulling down the gate voltage of the power stage transistor below its threshold voltage. Since the gate capacitor then is discharged, the gate capacitor has to be charged again by the constant current source. Similar to the above-described case

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when switching on the rectifier, the resistors conduct the inrush current, thereby limiting the current until the transistor becomes conductive.

5 According to an embodiment, the re-trigger circuit comprises a comparator configured to compare a delayed voltage based on the DC bus voltage with an un-delayed voltage based on the DC bus voltage, and to determine that a DC bus voltage jump has been occurred if the comparison results in a difference voltage higher than a threshold value.

10 According to an embodiment, the re-trigger circuit comprises a Schmitt trigger configured for detecting of a DC bus voltage jump.

The comparator may be for example a Schmitt trigger. The delay may be effected by a capacitor. For example, the first and the second input voltages for the comparator are the same when no jump happens. In case of a jump, however, the first input voltage changes
15 immediately to a new value and the second input first remains roughly at the same level than before the jump and then converges to the new value such that the input values are equal again. As long as the voltage difference starting at a point in time directly after the jump is higher than a threshold of the comparator, a signal is generated that pulls the gate of the transistor down.

20 According to an embodiment, the re-trigger circuit comprises a logic device to generate a control signal to turn the transistor off.

25 Instead of or supported by an analog solution such as using a capacitor as described above, a digital solution may be applied using, for example, a logic device such as a DSP, CPLD, FPGA or other logic components. In general, any logic device or arrangement of logic devices may be used.

30 According to an embodiment, the resistor, i.e. the inrush current limiting resistor parallel to the transistor, is an NTC, a PTC or a temperature independent power resistor.

The effect when using for example an NTC is that the resistance is high when switching on the rectifier because the NTC is cold, and the resistance gets lower when transiting to or during nominal operation as the NTC is getting hotter. Therefore, the inrush current is
35 severely limited initially, and the limitation decreases over time. Thus, the limitation is carried

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out in an effective way. However, also, for example, a PTC or a temperature independent power resistor may be used.

According to an embodiment, the transistor is a MOSFET transistor.

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Ideally, components with a threshold voltage U_{GS} (Gate-Source) of 4 ... 7 V and a saturation of for example U_{GS} of 10 V may be used. The MOSFET may be a SiC or a Si MOSFET.

10 According to a further aspect, a rectifier comprising an inrush current limiter circuit as described herein with a power stage is provided.

According to an embodiment, the power stage of the inrush current limiter circuit is arranged in a negative or a positive DC path of the rectifier.

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The choice between positive path and negative path may be based on the availability of suitable MOSFETs types on the market or on other design aspects. Preferably, the power stage is arranged in the negative path.

20 When the power stage is arranged in the negative path, the detection of the voltage jumps and the supply of the described circuits may be obtained by the positive DC bus voltage or obtained by voltages that are derived therefrom.

25 According to an embodiment, the rectifier is configured to supply the constant current source over a positive DC bus voltage of the rectifier.

As such, the drain of the MOSFET of the constant current source circuit may be a P-channel MOSFET whose Source is coupled through a resistor to the positive DC voltage and whose Drain is connected to the Gate of the power stage MOSFET.

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According to a further aspect, the rectifier is a capacitor-filtered bridge rectifier.

35 According to a further aspect, a method for limiting an inrush current of a rectifier flowing between a rectifying part of the rectifier and a filter capacitance is provided. wherein the inrush current limiter circuit comprises a power stage with a power stage resistor and a power stage transistor parallel to the resistor. The method comprises the steps of

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conducting, by the power stage resistor, an amount of the current in dependence on the state of the power stage transistor, and conducting, by the power stage transistor, an amount of the current in dependence on a charging of a gate capacitance of the power stage transistor.

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The method may further comprise that after switching on the rectifier the transistor is off and the resistor of the power stage conducts the inrush current. After charging the gate capacitance, the transistor of the power stage is switched on for conducting the current.

- 10 The method may further comprise discharging the gate capacitance in case of a voltage jump and further steps as described in this disclosure.

According to a further aspect, a use of an inrush current limiter circuit as described herein in a rectifier is provided. The inrush current limiter circuit may be used further in any energy

- 15 storage where the amount of stored energy is a function of the voltage over the storage. The inrush current manager supervises rapid increases of either of the both input voltages.

The features presented above and other features, aspects and advantages of the present invention will become better understood with reference to the accompanying figures and the following description. Identical or equivalent elements are in principle provided with the same reference signs.

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SHORT DESCRIPTION OF THE FIGURES

- 25 Fig. 1 shows a diagram of a rectifier comprising an inrush current limiter circuit according to an embodiment.

Fig. 2 shows plots of a simulation of the inrush current limiter circuit.

- 30 Fig. 3 shows a flow diagram of a method according to an embodiment.

DETAILED DESCRIPTION OF THE FIGURES

- 35 Fig. 1 shows a simplified schematics of a rectifier 100 comprising an inrush current limiter circuit 102, 104, 105 according to an embodiment. The rectifier comprises a rectifying stage 101 with a diode bridge 111, a constant current source 102 as one of the current limiter

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circuit blocks 102, 104, 105 with a transistor 106, a DC output stage 103 with a filtering capacitor 109, an inrush current block 105, which is referred to as power stage, and a further inrush current block 104, which is referred to as re-trigger circuit 104 in this disclosure. The rectifying stage 101 in Fig. 1 shows two bridge arrangements 112, 113. The first bridge
5 arrangement 112 may be connected to AC Main, the second one 113 to AC Main (UMain) or AC Auxiliary (UAux). The capacitor 109 of the output stage 103 filters the output voltage of the rectifying stage 101. UDC designates the positive DC bus, and GNDZ electrical ground.

When switching on the rectifier, the capacitor 109 will be loaded resulting in a high inrush
10 current. The same applies at any positive voltage jumps. In order to limit the inrush current, the inrush current block 105 is inserted, which comprises in the example of Fig. 1 a bank of parallel NTC resistors 108 and a transistor 107. When switching on the rectifier, transistor 107 is not yet conducting, and the NTC resistors 108 have a high resistance, hence limiting the inrush current. Meanwhile, the gate voltage of transistor 107 is slowly increased by the
15 current provided by the constant current source 102 that is controlled using transistor 106 resulting in an increase the current through transistor 107 until it is fully switched on. Therefore, the resistors 108 conduct the complete current when transistor 107 is turned off, a part of the current if the transistor is partly conducting, and nearly no current if transistor 107 is turned on such that quasi the full nominal current after the inrush period is conducted by
20 the transistor 107. The setting of an appropriate time constant allows balancing of the inrush current between the power MOSFET and the resistors in parallel.

That is, in a scenario where the rectifier 100 is switched on, the high inrush current is first limited by the high resistance of the cold NTC resistors. Contemporarily, the constant current
25 source 102 loads slowly the gate of transistor 107, such that the constant current source 102 enables a transition phase of the transistor between conducting no current and fully conducting. In this way, the NTC resistors 108 are released from conducting a high current when the temperature raises and the resistance is decreases, and thus getting too hot. On the other side, it is avoided that transistor 107 conducts the high inrush current in the first
30 phase after a voltage jump.

In operation, there may occur a further voltage jump, for example, due to a short outage, e.g. on grid side. For this case, the re-trigger circuit 104 is used to reset transistor 107. The trigger circuit 104 is connected to the power stage 105 at the UGS lines shown in Fig. 1. The
35 re-trigger circuit 104 comprises a comparator 110 that compares the voltage of a voltage divider and a voltage that is, in the example of Fig. 1, determined by a resistor and a

capacitor such that a positive voltage jump is detected. When detecting the voltage jump, the re-trigger circuit 102 lowers the gate voltage below the transistor threshold voltage such that the transistor 107 is switched off. Then, the procedure starts again by slowly charging the gate of transistor 107 by the constant current source 102.

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Fig. 2 shows the characteristic waveforms of a simulation with some scenarios applied to the circuit shown in Fig. 1.

Plot 202 depicts the input voltage with several voltage steps:

- 10 1) At $t = 0.1$ sec, 211: jump from 0V to 100Vdc,
- 2) At $t = 1.0$ sec, 212: jump from 100Vdc to 230Vac,
- 3) At $t = 2.0$ sec, 213: 1 second interruption of input voltage,
- 4) At $t = 3.0$ sec, 214: jump from 0V to 230Vac,
- 5) At $t = 3.85$ sec, 215: 100 ms interruption of the input voltage.

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Plot 204 shows the corresponding DC output voltage, plot 206 the input current, i.e. including the inrush current at the voltage jumps, and plot 208 the gate voltage of the current limiting power MOSFET 107 shown in Fig. 1.

- 20 At the start-up 211, the gate voltage 208 of transistor 107 is slowly increased by a constant, voltage independent, current that is regulated by the P-channel MOSFET 106 of the constant current source 102. Any following voltage jumps would not be limited by current state-of-the-art topologies. As shown in the plot 202, the input voltage increases at 212 and causes a drop in the gate-voltage 208 of transistor 107. This drop of the voltage is effected by the
- 25 comparator 110 that lowers the gate voltage below the transistor threshold voltage. This means, if any of the input lines (U_{MAIN} or U_{AUX}) has a positive delta of more than 15V (all filtered) the inrush current limiter turns on (or the gate-source voltage U_{GS} will be discharged to as low as gate-source threshold voltage $U_{GS_threshold}$) and current flows just trough the NTCs in the next moment. Consequently, the current limiting process restarts.
- 30 At 213, the DC voltage is zero such that the gate voltage drops to nearly zero and the AC voltage at 214 effects a rise of the gate voltage similar to the one shown for the start-up phase 211.

- Fig. 3 shows a flow diagram of a method 300 for limiting an inrush current of a rectifier
- 35 flowing between a rectifying part 101 of the rectifier and a filter capacitance 109, wherein the

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inrush current limiter circuit comprises a power stage 105 with a power stage resistor 108 and a power stage transistor 107 parallel to the resistor 108. The method comprises the following steps:

- 5 Conducting 302, by the power stage resistor 108, an amount of the current in dependence on the state of the power stage transistor 107.
Conducting 304, by the power stage transistor, an amount of the current in dependence on a charging of a gate capacitance of the power stage transistor 107.

- 10 Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from the study of the drawings, the disclosure, and the appended claims. In the claims, the word "comprising" does not exclude other elements or steps and the indefinite article "a" or "an" does not exclude a plurality. A single processor or other unit may fulfill the functions of several items or steps recited in the
- 15 claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope of the claims.

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List of reference signs

	100	rectifier
	101	rectifying part of the rectifier
5	102	constant current source
	103	DC output stage
	104	re-trigger circuit
	105	power stage
	106	transistor of the re-trigger circuit
10	107	power stage transistor
	108	power stage resistor
	109	filter capacitance
	110	comparator / Schmitt trigger
	111	diode bridge
15	112	first bridge arrangements of the rectifying part
	113	second bridge arrangements of the rectifying part
	202	plot of the input voltage
	204	plot of the DC output voltage
	206	plot of the input current
20	208	gate voltage of the transistor 107
	211	simulated first phase; initial phase/switching on the rectifier
	212	simulated second phase; voltage jump from 100Vdc to 230Vac
	213	simulated third phase; interruption of input voltage
	214	simulated fourth phase; jump from 0V to 230Vac
25	215	simulated fifth phase; interruption of the input voltage
	300	method
	302	first step of the method
	304	second step of the method

Claims:

1. Inrush current limiter circuit (102, 104, 105) for a rectifier (100), wherein the inrush current limiter circuit provides a flow of a current between a rectifying part (101) of the rectifier (100) and a filter capacitance (109), comprising
5 a power stage (105); wherein
the power stage (105) comprises a power stage resistor (108) and a power stage transistor (107) parallel to the power stage resistor (108);
wherein the power stage resistor (108) is configured to conduct an amount of the
10 current in dependence on the state of the power stage transistor (107); and
wherein the power stage transistor (107) is configured to conduct an amount of the current in dependence on a charging of a gate capacitance of the power stage transistor (107).
- 15 2. Inrush current limiter circuit (102, 104, 105) according to claim 1, further comprising a constant current source (102), wherein the constant current source (102) is configured for charging the gate capacitance of the power stage transistor (107).
- 20 3. Inrush current limiter circuit (102, 104, 105) according to claim 1, wherein the constant current source (102) is configured to charge the gate capacitance power stage transistor (107) according to a configured time constant.
- 25 4. Inrush current limiter circuit (102, 104, 105) according to claim 1 or 2, further comprising a re-trigger circuit (104); wherein the re-trigger circuit (104) is configured to detect a DC bus voltage jump, and to turn the transistor off if it has detected that there has been a DC bus voltage jump.
- 30 5. Inrush current limiter circuit (102, 104, 105) according to claim 4, wherein the re-trigger circuit (104) comprises a comparator (110) configured to compare a delayed voltage based on the DC bus voltage with an un-delayed voltage based on the DC bus voltage, and to determine that a DC bus voltage jump has been occurred if the comparison results in a difference voltage higher than a threshold value.
- 35 6. Inrush current limiter circuit (102, 104, 105) according to claim 4 or 5, wherein the re-trigger circuit (104) comprises a logic device to generate a control signal to turn the transistor (107) off.

7. Inrush current limiter circuit (102, 104, 105) according to any of the previous claims, wherein the re-trigger circuit (104) comprises a Schmitt trigger configured for detection of a DC bus voltage jump.
- 5 8. Inrush current limiter circuit (102, 104, 105) according to any of the previous claims, wherein the resistor (108) is an NTC, a PTC or a temperature independent power resistor.
9. Inrush current limiter circuit (102, 104, 105) according to any of the previous claims, wherein the transistor (107) of the power stage (105) is a MOSFET transistor.
- 10 10. Rectifier (100) comprising an inrush current limiter circuit (102, 104, 105) with a power stage (105) according to any of the previous claims.
11. Rectifier (100) according to the previous claim, wherein the power stage (105) of the inrush current limiter circuit (102, 104, 105) is arranged in a negative or a positive DC path of the rectifier (100).
- 15 12. Rectifier (100) according to any of claims 10 or 11, wherein the rectifier is configured to supply the constant current source (102) over a positive DC bus voltage of the rectifier (100).
- 20 13. Rectifier (100) according to any of claims 10 to 12, wherein the rectifier (100) is a capacitor-filtered bridge rectifier.
- 25 14. Method (300) for limiting an inrush current of a rectifier flowing between a rectifying part (101) of the rectifier and a filter capacitance (109), wherein the inrush current limiter circuit comprises a power stage (105) with a power stage resistor (108) and a power stage transistor (107) parallel to the resistor (108); wherein the method comprises the following steps:
- 30 conducting (302), by the power stage resistor (108), an amount of the current in dependence on the state of the power stage transistor (107); and
- conducting (304), by the power stage transistor, an amount of the current in dependence on a charging of a gate capacitance of the power stage transistor (107).

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15. Use of an inrush current limiter circuit (102, 104, 105) according to claims 1 to 9 in a rectifier (100) or an energy storage where an amount of stored energy is a function of a voltage over the storage.