Requirements on Power Electronics for converting Kitchen Appliances from AC to DC

Peter van Duijsen, Johan Woudstra, Diëgo Zuidervliet

***Abstract*—**The main power source for kitchen appliances for cooking and heating in Europe is natural gas. Since fossil fuels are limited, an energy transition is taking place from fossil fuel supply towards renewable energy such as solar and wind power. Kitchen appliances for cooking and heating have to be converted towards the use of electrical energy.

Although many kitchen appliances are available for electrical energy supply, a transition to a DC grid would have benefits regarding control, earth leakage protection and peak power usage.

Congestion management is solved via droop control. The bandwidth of droop control in DC grids is significantly higher compared to droop control in AC grids. Droop control enables load sharing during peak power demand. Earth leakage protection in an isolated grid enables early detection of earth faults, before they become critical.

Furthermore short circuit protection in a DC grid is implemented via a predictive rate of change of current di/dt measurement, isolating a fault before the short circuit current can grow.

The inrush current that exist when directly connecting the AC appliance to a DC grid, can be avoided by using a programmed current limiter which controls the level of the input current. Secondly this current limiter can be used to control the power level in appliances where current control is enough to control the application, such as the resistive heater in an oven.

Examples are given on the appliance of a inductive cooking and controlling the heater in an oven.

***Index Terms*—Kitchen Appliance, DC grid, Congestion Management, Inrush current, Droop control, Simulation**

1 INTRODUCTION

Kitchen appliances for cooking and heating are mostly powered by natural gas. A transition from natural gas for cooking and heating towards the use of renewable electrical energy is foreseen in the coming years. Although there is a widespread use of appliances working on electricity, the power requirements of these appliances is growing. The overall power consumption for kitchen appliances is taking place nearly simultaneously in all kitchens, thus peak power request are more or less happening at the same time. Natural gas could easily fulfill this peak power demand as the pressure of the natural gas distribution can be increased during peak demands. The peak demand for electric power was not taking into consideration when the electric power distribution grid was designed. Most power grids are designed for average power consumption by light bulbs, refrigerators and every now and then a soccer match on television.

Typical power demands from kitchen appliances are cooking and heating in an oven. Those require the maximum power available and will leave no room for any extra power demand. In a standard household connected to an AC grid we are aware of the fact that too many appliances working at the same time could be the cause of a sudden failure and shutdown. Especially in older households if was known not to start the water cooker, when the oven was set to heat at its maximum temperature.

With the transition from natural gas to electrical energy for kitchen appliances, there is a chance to overcome this shortage of electrical power by using congestion management [1]. The appliances are allowed to use just that amount of power that is available to prevent an excessive over-current failure resulting in a shutdown of the AC grid in the house.

2 CONGESTION MANAGEMENT

When the grid is used at its maximum power level, there is no room for excessive extra power, not even for a short time. Congestion Management [1] manages the flow and of electrical power and thereby reduces power levels at the appliances in order to stay below the limit of the maximum allowed power.

Let us consider an example. Suppose the oven is operating at its maximum power and this is the maximum power available through the grid. Turning on a water cooker, would simply ask for too much power and the fuse will blow. If there would be congestion management, both appliances would be allowed to continue operating, but at a lower power level. There must be some sort of communication in the grid to tell each appliance that it has to reduce its power level, in order to stay below the maximum peak power allowed in that certain grid. In its most simplest and technically elegant way this is Droop Control [6].

2.1 Droop control

The value of the dc grid voltage determines the available power that can be consumed. Depending on the DC voltage an appliance can consume more or less power. A dc voltage below the nominal value means there is a shortage of power and an appliance has to lower the consumption. A DC voltage above the nominal voltage means that there is surplus of power and the appliance can consume the maximum power if required. In Fig 1 the droop control function for a resistive heater is displayed.

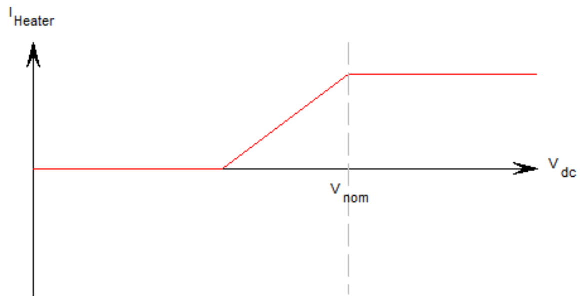

Fig. 1. Droop control of a resistive heater.

The droop constant *R* defines the slope of the droop controller. Each appliance has its own droop controller and each droop controller has its own parameters. Depending on the requirements of the appliance, the droop constant *R* can be increased or decreased. For example, a resistive heater can have a low droop constant *R*, while a hand-held appliance that is used for a short period, can have a larger droop constant *R*. In this way the hand-held appliance can be operated for a short time period, where the heater is limited in its consumption. The total power consumption is thereby not increased but remains at its nominal value.

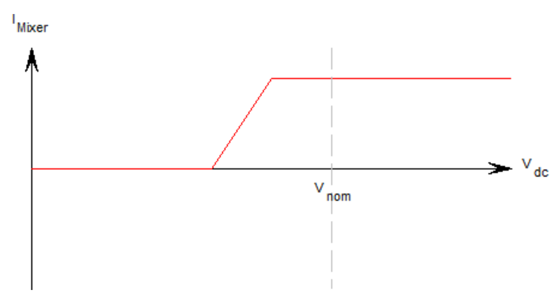

Fig. 2. Droop control of a hand-held mixer with higher priority than the heater from Fig1.

For each application or supply a droop controller can be programmed inside the grid manager. For example in Fig 3 the droop control for a battery storage is shown. In case the DC voltage will get lower because of higher demands, the battery will supply power to the grid, as soon as the DC voltage is beyond the nominal voltage, the battery will charge itself.

The State of Charge [SoC] of the battery determines the sloop of the droop control $R_{Droop(SoC)}$

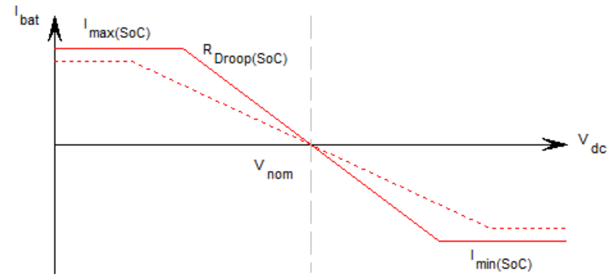

Fig. 3. Droop control for charging an discharging a battery. Positive power means discharging the battery, negative power means charging.

2.2 Communication

Communication with every droop controller can be implemented in various ways. Most likely Home Automation systems will be used, but also the IoT via Wifi, or IoT via 5G is possible

3 GRID MANAGER

The task of the Grid Manager is to implement DC supply, protection and monitoring of the DC grid. Electrical power supplied to the DC grid comes either from an AC distribution grid, a DC distribution grid, regenerative sources like solar, or from local battery storage. Each of these aforementioned supplies can directly be connected to the DC grid as shown in Fig 4, or all can be connected to a grid manager. The advantage of connecting all supply and appliances via a grid manager is the protection for short circuit and earth leakage, that can be implemented in a grid manager [6]

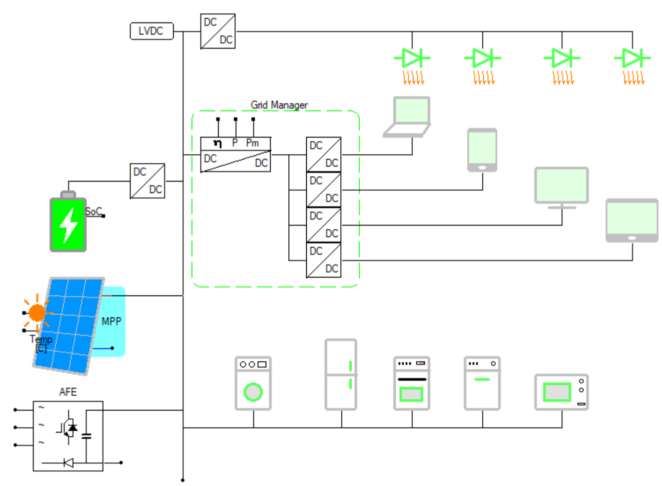

Fig. 4. Grid manager for controlling users on the DC grid

4 SHORT CIRCUIT PROTECTION

Short-circuit protection is not only defined by the maximum current that is allowed before a circuit breaker switches off the load, but on the rise of the current. In [8], [9], [10], [11] the rate of change of current is measured and before the maximum current is reached, the circuit breaker switches off the load.

A typical solid state circuit breaker using a SiC JFET is reported in [12], where the normally-on of the JFET is used to have a low on state resistance without gate voltage in normal operation. During short circuit, because of the increase of the current beyond a maximum value, the gate of the JFET is triggered and thereby the current is limited.

5 APPLIANCE AC INPUT

There are basically two different ways the AC input is used in the appliances; AC voltage controller or a rectifier with DC link capacitor and DCAC inverter.

A. AC voltage controller

The AC voltage controller, mostly a SCR or TRIAC that controls the average AC current by phase control, is a common robust and price-worth solution. It is used for driving universal motors and for controlling the average current in resistive heaters. The disadvantage are the large harmonics caused by the phase control and therefore large filters are required.

To connect these appliances mostly means changing the type of motor and including power electronics for the control as discussed in the next subsection.

B. DC link

AC appliances that already have power electronics inside have a common mode filter and rectifier followed by an electrolyte capacitor. To connect these appliances to a DC grid, mainly involves control of the power at the DC side of the applications. In the section Examples, some typical control methods are discussed.

Figure 5 shows a typical DC ready AC appliance input, that can handle a DC input. The resistive load in this schematic is the appliance itself.

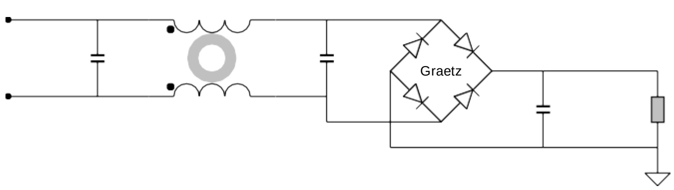

Fig. 5. Typical input connection of an AC appliance.

6 INRUSH PROTECTION

If we directly connect the AC application to the AC grid, there is no numerous inrush, since the AC voltage is varying slowly compared to the delay time of the internal circuit $\tau = R \cdot C = 10 \cdot 200\mu = 2ms$, see Fig 6.

However if we directly connect to the DC grid, a high inrush current appears which charges the internal capacitors (Fig 7).

If we limit the input current, the inrush is limited. In Fig 8 the inrush current is limited by power electronics. The simulation of the input current shows that the inrush is during the first 4ms, while power demand starts at 5ms.

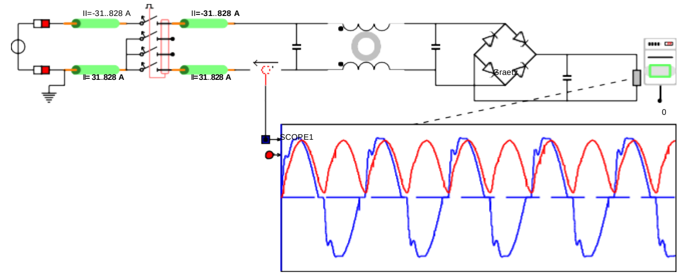

Fig. 6. No inrush, since the AC voltage is not changing stepwise.

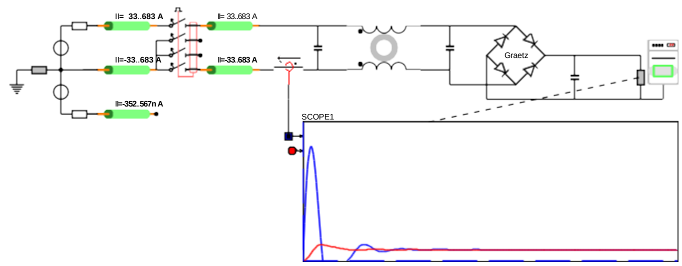

Fig. 7. DC inrush current[blue] and appliance current[red].

7 EARTH LEAKAGE PROTECTION

In an isolated grid an earth leakage can be detected before it becomes a failure. Mostly earth leakage starts as a small current, well below the critical harmful level. A warning signal can be issued for maintenance, before switching off the branch where the earth leakage is detected. In many cases the branch can be left operating without switching off if the earth leakage current is below the safety level. Earth leakage can be detected in two different ways an depends on whether an isolated or non-isolated grid is used.

7.1 Non-Isolated grid

If one of the lines in a grid is connected to ground, for example via common neutral in a distribution transformer, the grid is not electrically isolated from earth. A residual current [RCD] is measured by summing all ingoing and outgoing currents into the grid. If the sum is unequal to zero, there is a leakage of current towards earth. RCD is common in AC house installations. Only when the residual current exceeds a certain threshold, the RCD circuit breaker immediately disconnects the grid. The measurement error is dependent on the quality of the difference measurement.

7.2 Isolated grid

Earth leakage in an isolated grid can be detected premature by measuring the flow of current between the lines of the grid and the earth. The grid lines are connected via a high-ohmic sense resistor to earth. Since only currents can flow that can circulated through a fault to earth, even the smallest beginning earth leakage can be detected, see Fig 9. There is little error in the measurement, since the sensing is designed for sensing small currents in contrast to the high current sensors that have to measure small differences between high currents in the RCD.

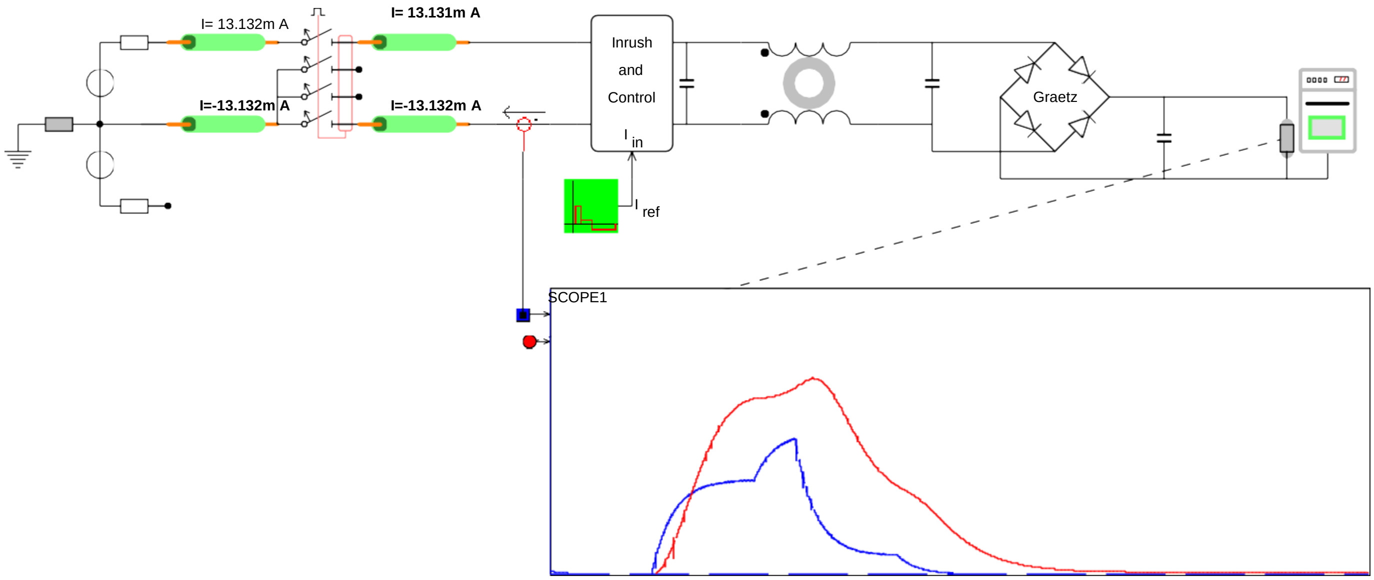

Fig. 8. No inrush, since the input current is controlled.

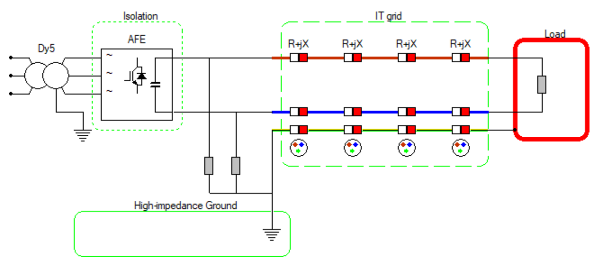

Fig. 9. Galvanic isolation in the Active Front End creates an isolated IT DC grid.

8 DCDC CONVERSION

To control the amount of power used by the appliance, a DCDC converter is required that can either control the output voltage to the appliance or can limit the current through the appliance. Depending on the appliance there are typically two types of control, current control for resistive heaters and voltage control for appliances that have power electronics such as inverters for motor control and resonant converters for inductive heaters.

8.1 Current Control

Resistive heaters are common in electrical ovens and boilers. If the current through the resistive heater can be controlled, the temperature can be controlled. The DCDC converter for current control automatically contains a short circuit protection and maximum current limiter. For example in [7] the maximum armature current in an universal motor is controlled using a single buck converter with peak current control.

8.2 Voltage Control

Thanks to the rise of the brushless machines in kitchen appliances, also inverters operating from a DC link became common. Since the inverter takes care of controlling the electric motor, the only concern is the voltage level of the inverter. A typical AC 230V, 50Hz will give a rectified voltage of maximum 326 volt. If connected to a DC grid of 350V or 380V, a DCDC conversion from the grid voltage to this 326 volt is required.

8.3 Harmonics

To reduce the amount of harmonics on the DC grid, interleaving can be used to reduce the harmonic content and thereby reducing the size of the input filters. In Fig 10 the input current of an interleaved buck converter with four interleaved converters is compared to a single stage buck converter. The scope shows the input current waveform for both converters. The interleaved buck converter clearly shows a lower ripple. Increasing the number of stage can further reduce the input ripple, although the reduction gets smaller with increasing number of stages [13]

9 EXAMPLES

A number of kitchen appliances are converted towards an DC grid. In some cases an extra DCDC converter had to be build, in other cases, regulating the amount of power consumption became necessary. The following sections show some typical examples.

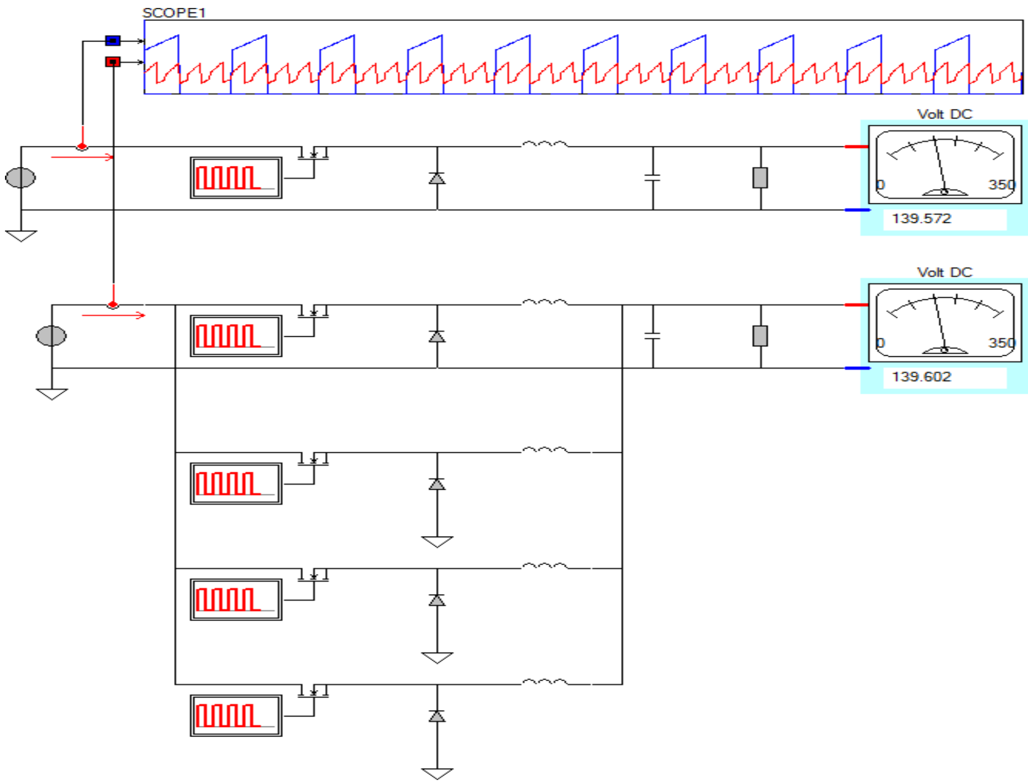

Fig. 10. Interleaved buck converter. Scope 1 shows the input current for both converters, that have the same output voltage and load power.

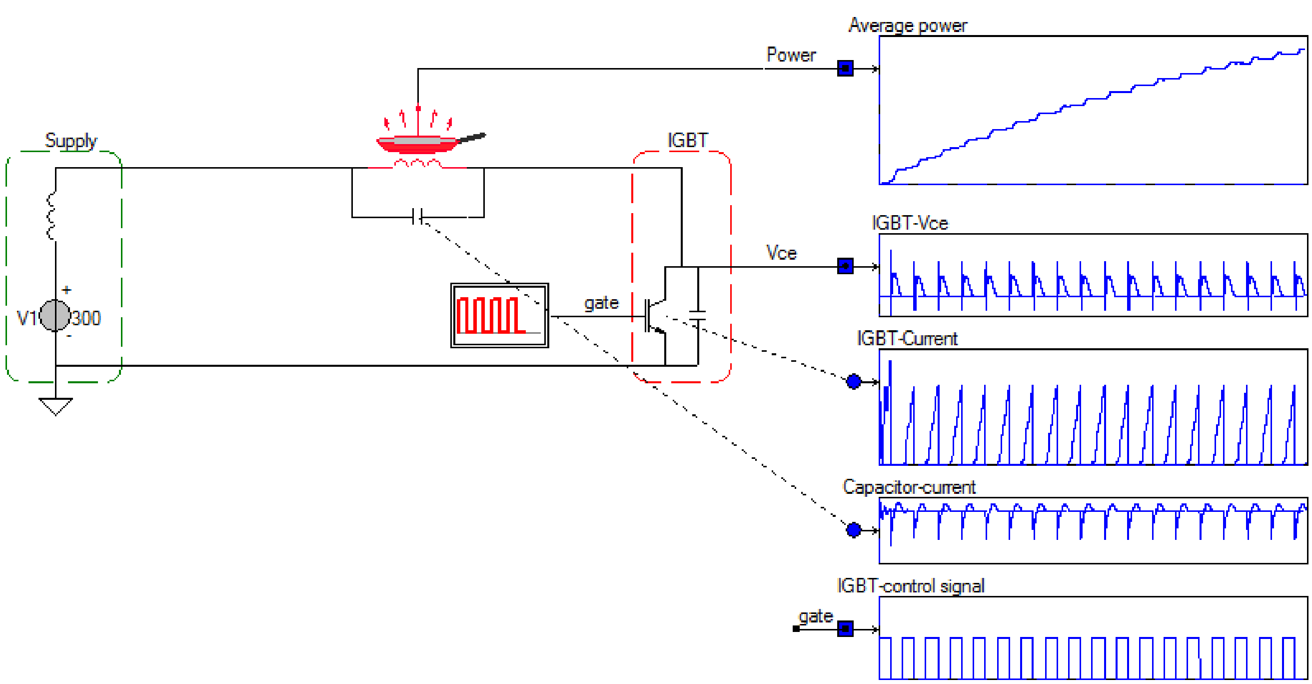

Fig. 11. Inductive cooking using a Single Ended resonant converter.

9.1 Inductive Cooking

Inductive cooking is based on a resonant converter. The high frequency current through the coil in the inductive cooker, induces a secondary current in the bottom of the pan. The resonant converter operates from a DC voltage and is therefore easily applicable to be converted towards a DC grid. The duration of the gating pulse of the IGBT in Fig 11 controls the amount of power that is transferred.

In Fig 12 the water is heated from a DC supply and the resonant voltage and current are shown in Fig 13.

Fig. 12. DC grid (+350V) supplying an inductive cooker. The circuit is limited on a cooking level of 1kW.

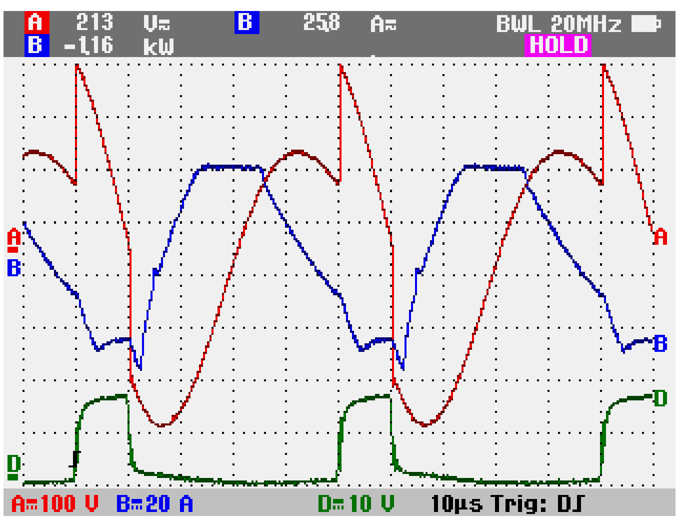

Fig. 13. Resonant current(blue), voltage(red) and gating signal(green).

9.2 Electric heating/oven

Electric heating is mostly done via a resistive heater. Simply regulating the current through a resistor gives a controllable temperature. In an AC grid the current is controlled using a Triac or SCR, see Fig 14. Since this is not possible in a DC grid, there is no zero crossing to turn off the Triac, a DCDC converter with current control is required.

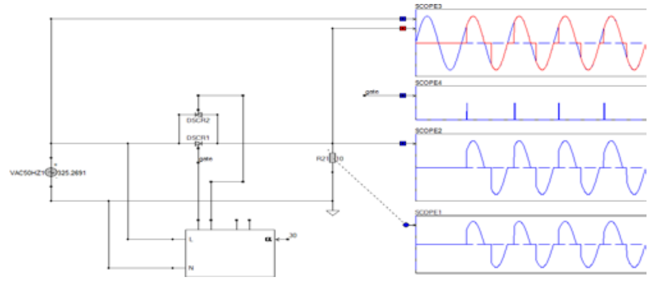

Fig. 14. Thyristor controlled AC voltage to regulate current through a resistive heater for an AC grid.

A typical Mosfet controlled current regulator as used in [7] can be applied here. Fig 17 shows the principal simulation. The Mosfet is turned on by the internal clock of the control IC. As soon as the current reaches threshold value, the Mosfet is turned off. The upper scope in Fig 17 shows the current through the heater and the lower scope shows the current through the Mosfet. The inductor with freewheeling diode is used to create an average lower current in the same way a buck converter operates.

In Fig 15 the water is heated with the use of a resistive heater based [7] on the circuit from Fig 17. The voltage and current are shown in Fig 16.

Fig. 15. DC grid (+350V) supplying a resistive heater with a current regulated circuit. The circuit is limited on a 1kW load.

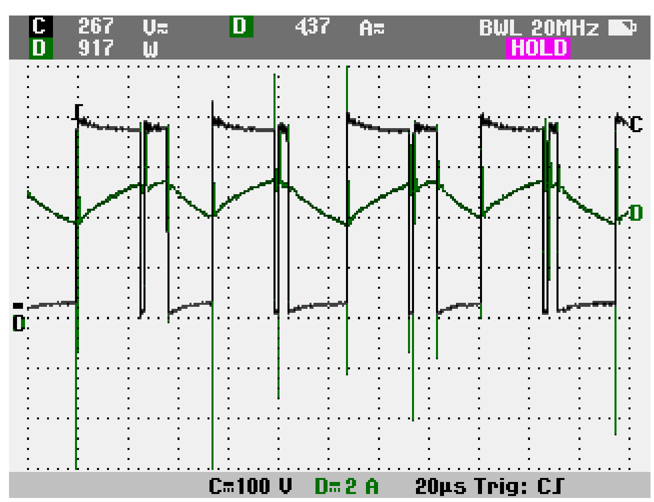

Fig. 16. Controlled current through a resistive heater for a DC grid.

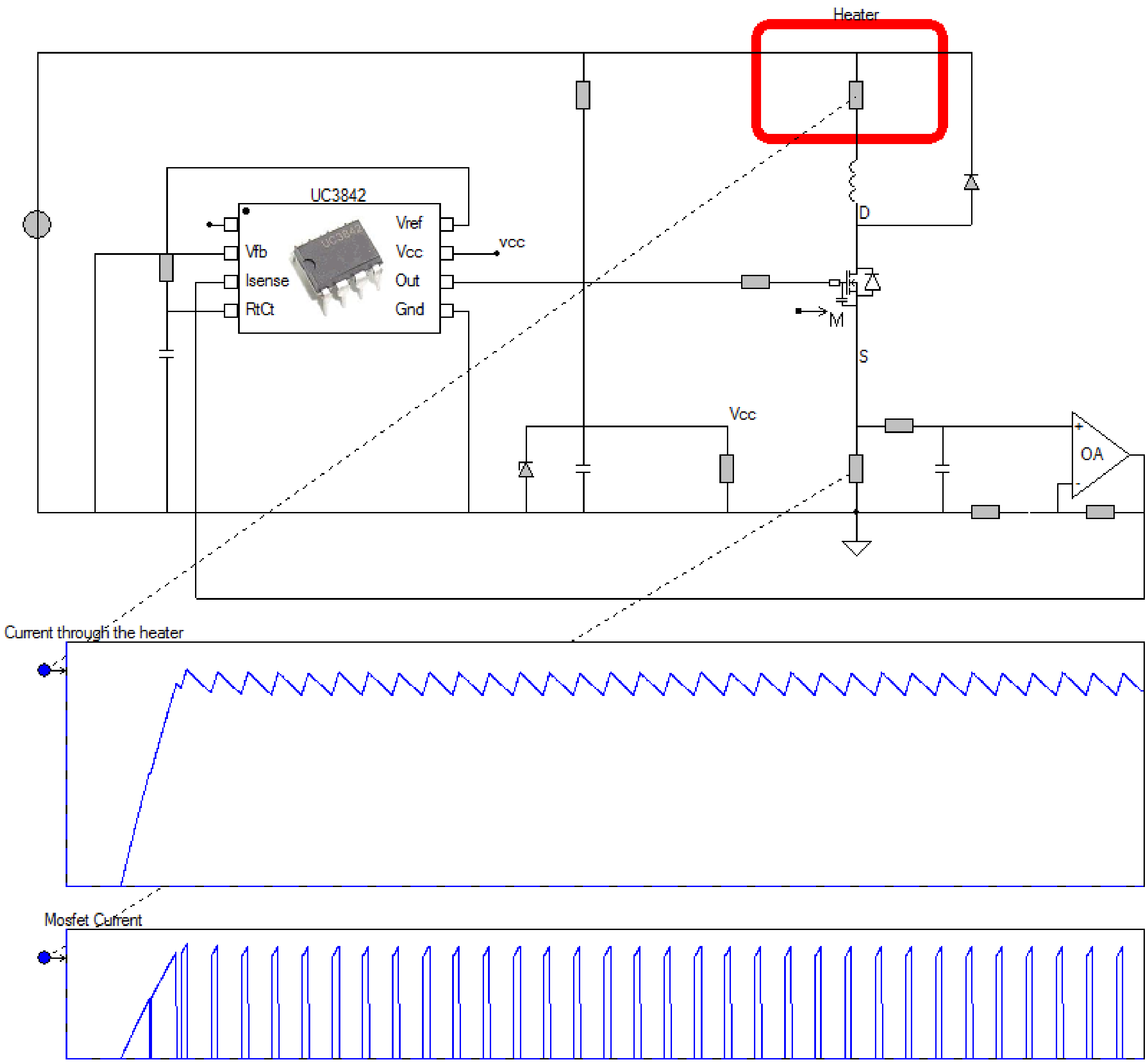

Fig. 17. Mosfet controlled current through a resistive heater.

CONCLUSIONS

Conversion from AC grid electrical power supply to DC grid with droop control and active protection can solve the problem of peak power shortage. Congestion Management has to be applied in the form of a simple low level droop control. Protection for short circuit can be implemented by predictive excessive di/dt current rise. Protection against earth leakage is implemented by applying an isolated grid. Earth leakage can be detected at an early stage, before harmful current can flow. Droop control, inrush current limitation and power control are implemented using a single DCDC converter between each appliance and the DC grid.

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