Active damping of oscillations in LC-filter for line connected, current controlled, PWM voltage source converters

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Abstract

Presented is a method for active damping of oscillations between line reactance and filter capacitors in LC-filter for line connected current controlled pulse width modulated (PWM) voltage source converters. The idea is to include closed loop feedback control that controls the capacitor voltage oscillations to zero by adding damping components to the current references. The voltage oscillations are calculated from manipulated measured filter capacitor voltages (using phase locked loop (PLL), Park- and inverse Park-transformation, low pass filtering and summation).

The advantage of such an approach is that the higher oscillation frequency components can be controlled independently of remaining converter control. It is only the higher frequency components that are controlled by this additional closed loop voltage control. Further, additional measurements and increased converter rating are not required.

Simulations and measurements presented in this paper show that the method works as intended. If active damping is implemented, then the voltage quality at the point of converter connection is maintained also in cases were filter oscillations is to be expected when the LC-filter is introduced.

Introduction

The basis for the discussion is a current controlled, line connected, PWM voltage source converter as shown in Figure 1 (used for instance as active rectifier / inverter, STATCOM or active filter).

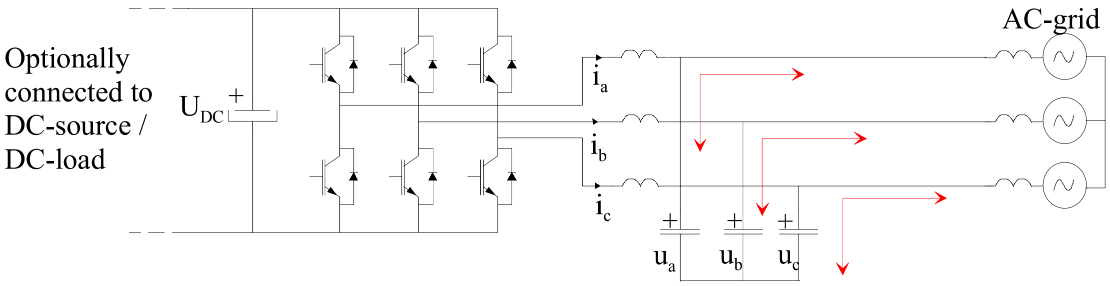


Figure 1 Power circuit of grid connected voltage source PWM converter with LC-filter. The red arrows illustrate the type of oscillations focused in this paper (between filter capacitor and grid reactance)

In most cases, a low pass filter at converter terminals is needed in order to fulfil power quality requirements. A LC-filter is a common method to reduce the switching ripple problem. The LC-filter however, introduces risk of oscillations in converter terminal voltage due to resonance between LC-filter capacitor and AC-grid reactance (illustrated by the red arrows in the Figure 1). Oscillations can be initiated by load changes or by periodic disturbances in the grid (e.g. thyristor rectifiers).

A traditional current controlled PWM converter uses the filter inductor current in the feedback loop and will therefore have no direct control of the current flowing between filter capacitor and AC-network. The damping of oscillations will mainly depend on losses in filter capacitor and of losses in upstream supply transformers / cables / generators. The system damping will be less for low natural frequencies due to frequency dependent losses. Filter oscillations will therefore be a larger problem when the natural frequency of the oscillation is low. This will typical imply that the worst cases will be those were the converter rating becomes comparable to the upstream transformer (or generator) rating. A typical example is emergency operation of isolated grids were converter ratings may become comparable to emergency generator ratings.

Methods for damping of oscillations have been published. The approach in reference [1] is to add lead-lag compensated feedback from measured capacitor voltage directly to the pulse with modulator. References [2] and [4] uses a damping strategy in which the converter is controlled such that virtual resistor(s) damps out the oscillations. The active damping method presented in this paper is related to these methods since the effect of the closed loop control presented here is much the same as a frequency dependent resistor in parallel to the filter capacitor.

Reference [3] presents a motor-drive damping method that is also related to the method presented in this paper. Capacitor voltage measurement is used for modification of current references. A synchronous rotating reference frame is however not applied in reference [3].

This paper will present an alternative method for active damping of filter capacitor voltage oscillations. The idea is to include closed loop feedback control that controls the capacitor voltage oscillations to zero by adding damping components to the current references.

Description of control system and active damping method

Basic control system

The active damping is an “add-on” feature. The basis is a current controlled PWM converter where filter inductor currents, filter capacitor voltages and DC-link voltage are measured ($i_{a/b/c}$, $u_{a/b/c}$ and U_{DC} in Figure 1). The basic control system is drawn with black lines in Figure 2.

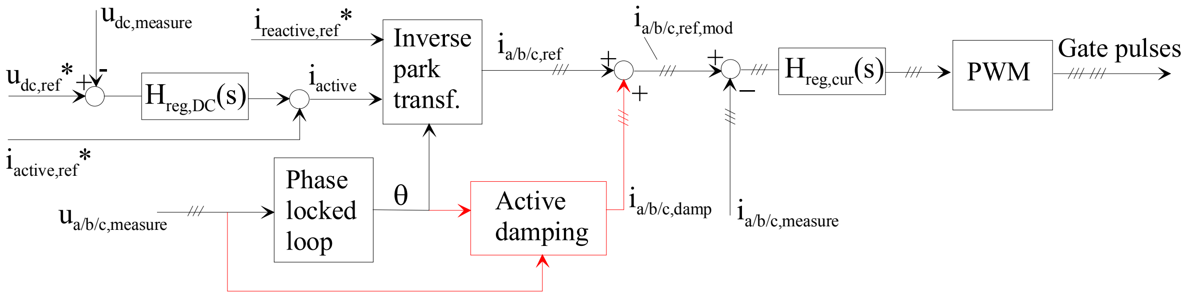


Figure 2 Control circuit including the active damping (red lines / box)

The current measurements are used in a closed loop current controller (one for each phase). The capacitor voltage measurements are input to a phase locked loop that synchronizes the current reference generation. The DC-link voltage measurement is used in a closed loop voltage controller that keeps the DC-link voltage at a desired level by controlling the active converter current.

This is a general control system which is applicable in different types of application like active rectifier / inverter, STATCOM and active filter. Current control is often preferred in such applications due to stability advantages. The most important application dependent differences will be the type of equipment connected to the DC-link and the way the active and reactive current references ($i_{reactive,ref}^*$ and $i_{active,ref}^*$) are generated.

Active damping

The idea is to include closed loop feedback control that controls the capacitor voltage oscillations to zero by adding damping components to the current references. The control loop principle is illustrated in Figure 2. The red coloured lines in the figure shows the additional block and signals introduced by the active damping. The active damping introduces no need for additional measurements.

The basic principle can be summarized as follows:

- The oscillating component of the capacitor voltage is extracted (the non-fundamental component)
- The error in the capacitor voltage is found by subtracting the oscillating component from its reference (which equals zero)
- The error is amplified and added to the reference signal for the current controller.

The simplest error amplifier is a proportional error-controller. Only this type of error amplifier is used in the examples presented in this paper.

A critical task in the presented controller structure is the detection of filter capacitor voltage oscillations. Ideally, the three signals $u_{a/b/c,oscillation}$ should be equal to the difference between the actual voltage waveform and a pure fundamental positive sequence voltage waveform.

Note: One may optionally consider negative sequence components in the voltage as an oscillation that should be compensated or one may ignore the negative sequence component (see comment later in this paper)

The selected method for oscillation detection in this paper is to extract the positive sequence fundamental voltage in each phase and subtract this fundamental voltage from the actual measured voltage. The result is then the detected oscillation voltage $u_{a/b/c,oscillation}$. The principle is illustrated in Figure 3.

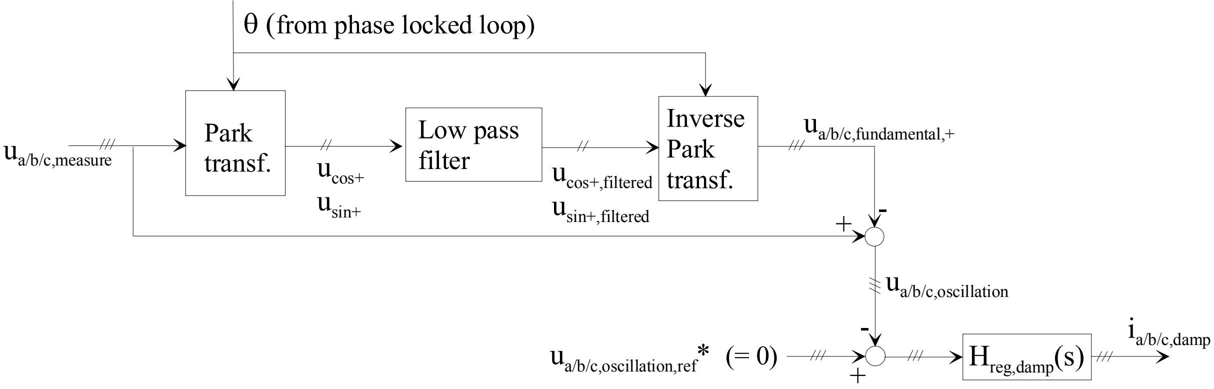


Figure 3 Block diagram, which illustrate the internal of the active damping block in Figure 2.

The time constant of the low pass filters influences the performance of the active damping during slows transients and also the performance when negative sequence voltage components are present. The filter must therefore be selected according to desired behaviour (application dependent).

The performance of the voltage oscillation detection is illustrated in Figure 4 (simulation, all control loops opened). The plot shows how voltage oscillations after a load step are detected. The low pass filter time constants used in this simulation is 5.0 ms.

Intuitively one could perhaps expect that large low pass filter time constants give the best result. However, a large time constant also pick up fundamental voltage variations. This is not necessarily desired (application dependent).

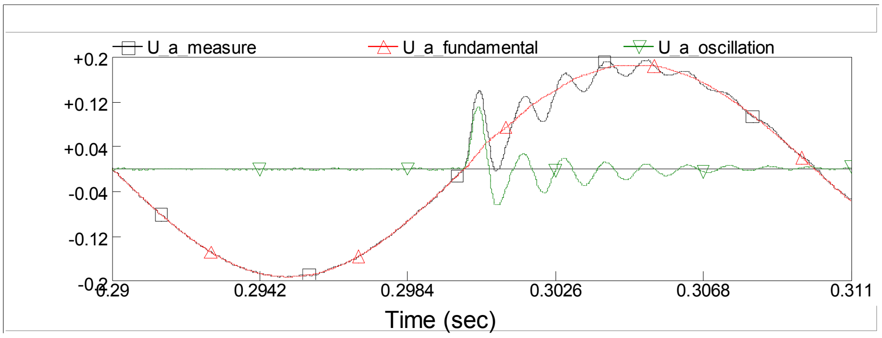


Figure 4 Illustration of simulated voltage oscillation detection with low pass filter time constant equal to 5 ms. The black curve shows the simulated filter capacitor voltage ($U_{a,measure}$, kV). The red curve shows the fundamental positive sequence component ($U_{a,fundamental+}$, kV) and the green curve is the detected voltage oscillation ($U_{a,oscillation}$, kV)

Demonstration by simulation

A simulation model has been established in the PSCAD/EMTDC simulation software [5]. The model has been verified by measurements on a laboratory prototype. The model is used here to demonstrate the effect of the active damping method.

Case No.1: Simulation of reactive power flow step reversal

The selected case for simulation is shown in Figure 5. A PWM converter with LC-filter is connected to a weak AC-bus.

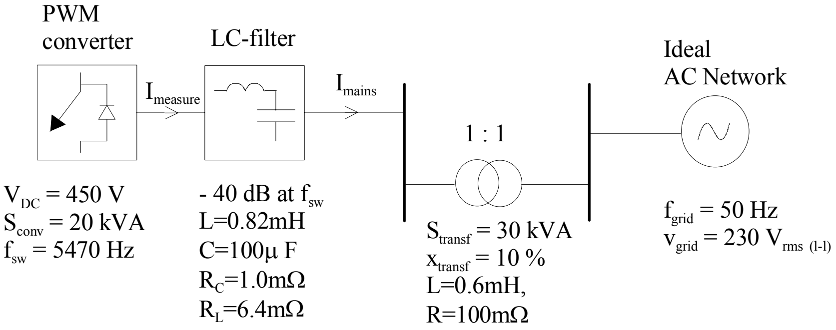
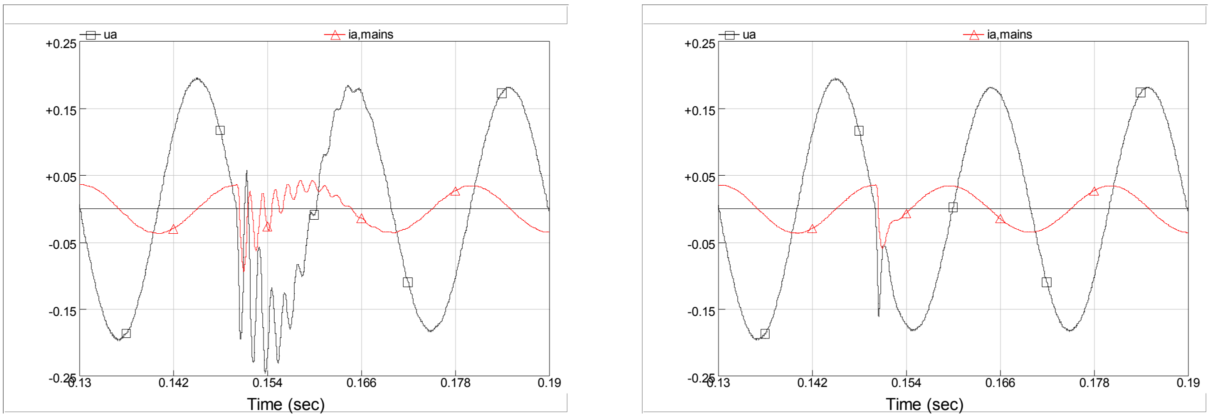


Figure 5 Single line drawing of AC network used for simulation of reactive power flow step reversal (full three-phase model is used in the simulation). Note that the PWM converter rating is in the same range as the upstream transformer.

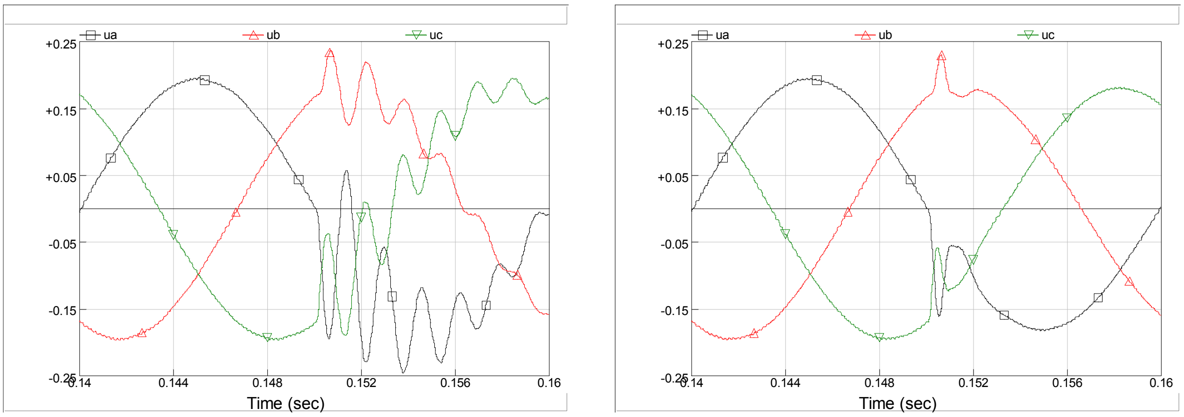
The simulation model has been used to test the proposed principle of active damping. The performance is demonstrated in Figure 6 to Figure 8 were results with active damping disabled (a) and enabled (b) are presented. The simulated case is a step reversal of the reactive current reference. The reference for current $I_{measure}$ is stepped such that the steady state current I_{mains} steps from $35A_{peak}$ lag to lead. The step initiates oscillations between AC-network reactance and filter capacitor (seen in Figure 6a and Figure 7a). Other types of disturbances, as sudden load changes, will initiate similar oscillations.

The effect of the active damping is clearly seen in Figure 6b and Figure 7b. The oscillations are damped out very fast in the case were the active damping is enabled. Figure 8 shows how the current reference for phase a, is modified by the active damping part of the controller.



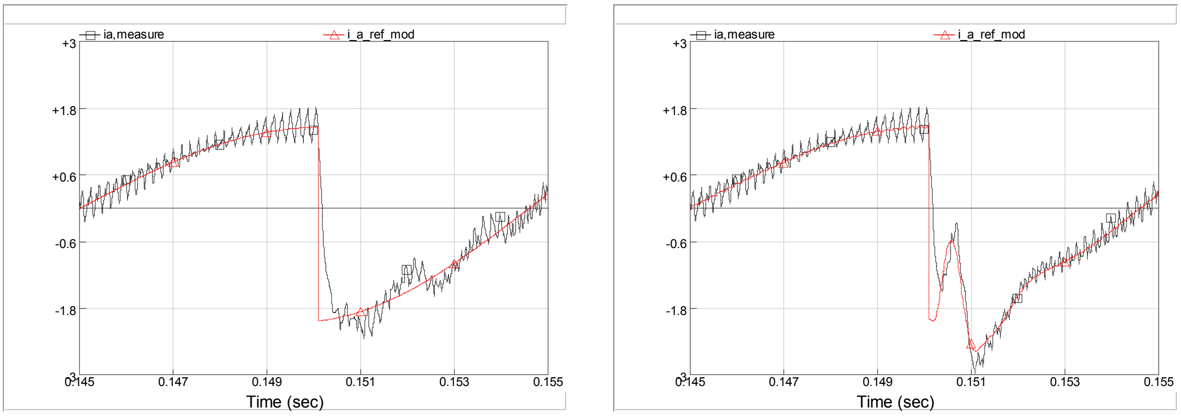
(a) (b)

Figure 6 Simulated filter capacitor voltage ($u_{a,}$ kV) and current into the AC-grid ($i_{a,mains}$ kA) before and after step reversal of reactive current reference from $35A_{peak}$ lag to $35A_{peak}$ lead. Damping control is disabled in (a) and enabled in (b)



(a) (b)

Figure 7 Simulated filter capacitor voltages ($u_{a,}$ $u_{b,}$ $u_{c,}$ kV) before and after step reversal of reactive current from $35A_{peak}$ lag to lead. Damping control is disabled in (a) and enabled in (b)



(a) (b)

Figure 8 Simulated current ($i_{a,measure}$) and current reference ($i_{a,ref,mod}$) for phase a before and after step reversal of reactive current from $35A_{peak}$ lag to $35A_{peak}$ lead. Damping control is disabled in (a) and enabled in (b). (Scaling: 1.0 corresponds to 20A).

Case No.2: Simulation of three phase diode rectifier parallel load

The second case to be demonstrated by simulations is the damping of oscillations caused by a diode rectifier load connected to the same bus as the PWM-converter. The case is illustrated in Figure 9. Note that the diode rectifier is directly connected to the bus without any commutating reactance. The following operating condition is simulated:

- The reactive current reference of the converter is set such that the reactive power flow from converter/LC-filter into bus A equals 35A peak (24.7 A rms).
- A three-phase diode rectifier with constant DC current (25 A, 7.8 kW) is connected at bus A
- The active damping is initially disabled and is enabled at time 0.15.

Resulting simulated voltages and currents are presented in Figure 10. It is clearly seen that the oscillations in current and voltages are reduced after the active damping is enabled at time 0.15.

It is also seen that the damping does not remove harmonics in voltages and currents. This is as expected since what is implemented is active damping and not an active filter.

Figure 11 shows how the active damping in the case shown in Figure 10 modifies the current reference in order to damp out the oscillations trigged by each diode rectifier commutation. It is seen that the active damping gives only a slightly modified current reference after each diode rectifier commutation. This small modification is however enough to improve the voltage at bus A and also to reduce oscillations in current between bus A and B.

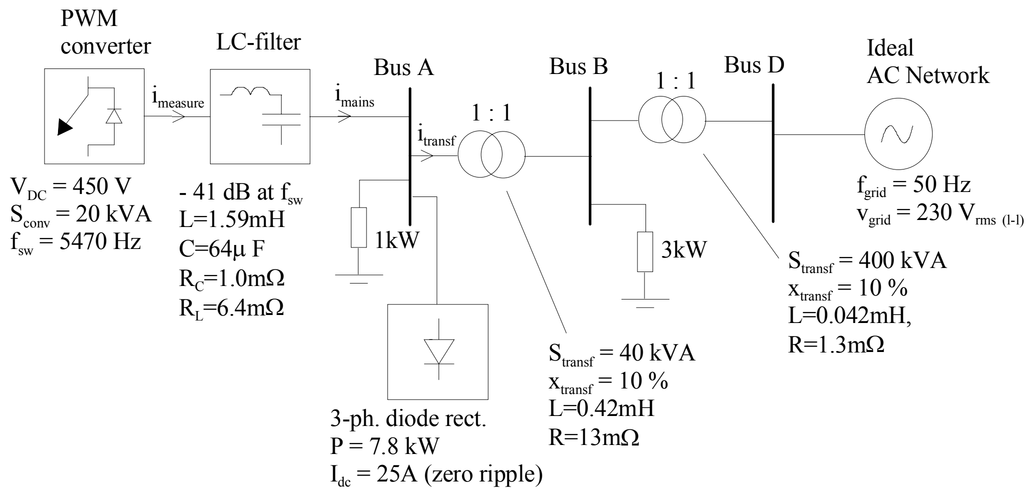


Figure 9 Three-phase diode rectifier connected at bus A

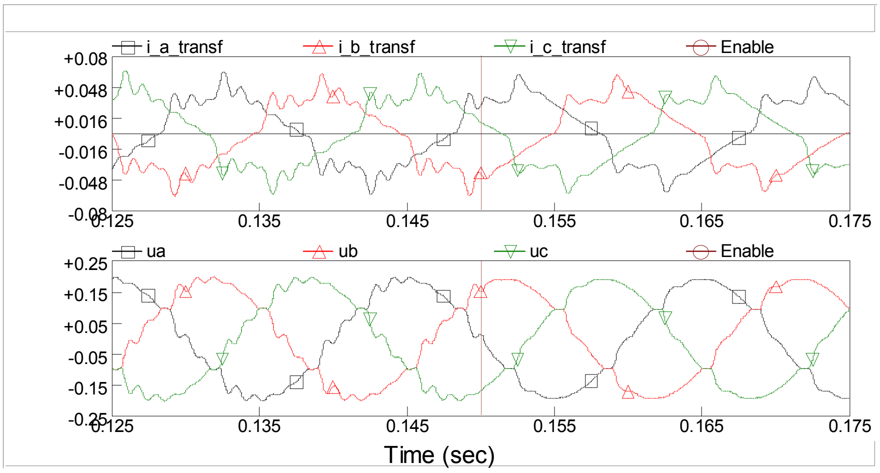


Figure 10 Three-phase diode rectifier connected at bus A. Active damping enabled at time 0.15 (marked by vertical line). Upper plot shows simulated current (kA) flowing between bus A and B (I_{transf}). Lower plot shows filter capacitor phase voltages (kV).

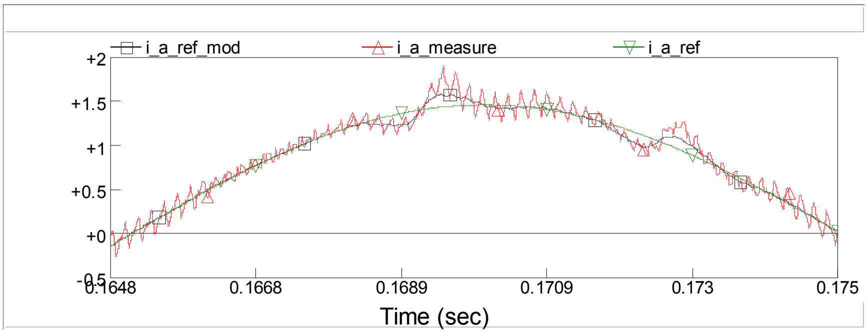


Figure 11 Three-phase diode rectifier connected at bus A. Active damping enabled. The figure shows half a period of the simulated current reference ($i_{a,ref}$) before adding the damping signal (green curve), the simulated current reference including contribution from active damping ($i_{a,ref,mod}$)(black curve) and the resulting simulated current in the filter inductor ($i_{a,measure}$) (red) (Scaling: 1.0 corresponds to 20A).

Demonstration on laboratory prototype

Power circuit

The damping method has also been tested on a 20 kW IGBT converter prototype connected to a weak AC-bus. The experimental set-up is illustrated in Figure 12. The main technical data is shown in the figure.

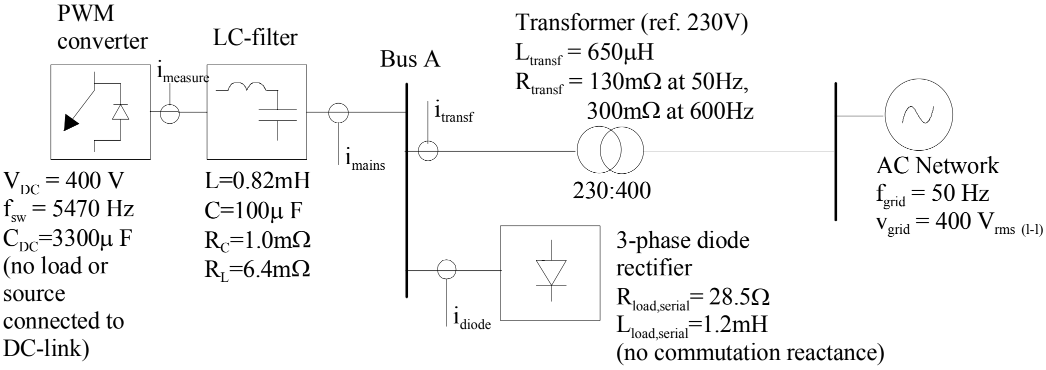


Figure 12 Experimental set-up and main technical data.

Control implementation

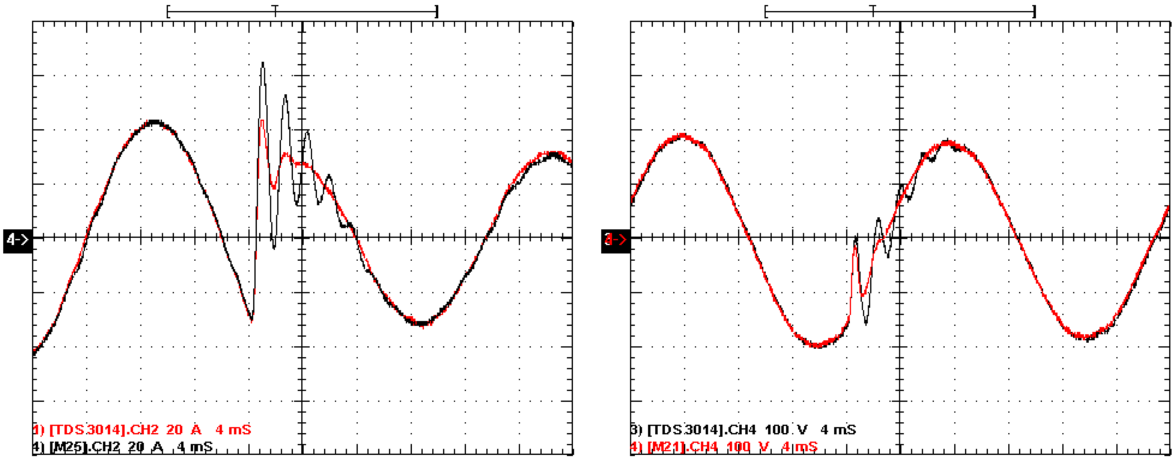
The main part of the control system is implemented in a microcontroller (Infineon C167-CR at 20 MHz). For the time being the fast control loops are implemented as analogue circuits. The active damping is implemented partly in the microprocessor (extraction of fundamental component) and partly as analogue circuits.

Case No.3: Damping of oscillations after load transients (measurements)

The first case to be demonstrated by laboratory measurements is the damping effect on oscillations after a load transient. The diode rectifier is in the first case disconnected. The reactive current reference is stepped from $35A_{peak}$ lag to $35A_{peak}$ lead. This step provokes oscillations.

A direct comparison of measurements for the cases active damping disabled and active damping enabled is presented in Figure 13a (currents) and Figure 13b (voltages). The measurements show that the active damping is working as intended.

Note that the filter capacitor also delivers reactive current. The reactive current flowing into bus A (i_{mains}) will therefore be larger and less than $35A_{peak}$ depending on reactive power flow direction. This is because it is the reference for current $i_{measure}$ (not i_{mains}) that is stepped. (Note however that it is opposite in example case No.1 (i_{mains} are stepped)).



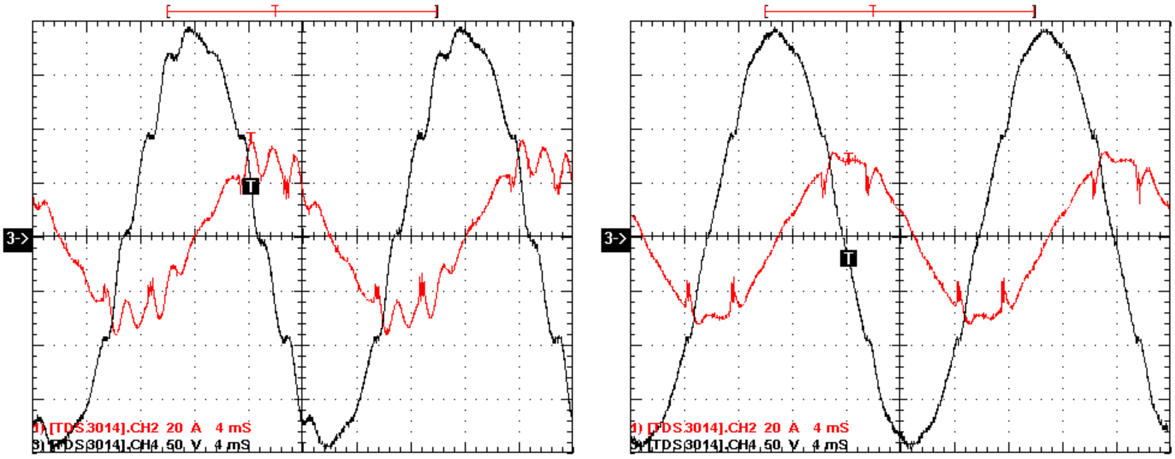
(a) (b)

Figure 13 (a) show measured transformer current (i_{transf}) and (b) show measured phase voltage at bus A during step reversal of PWM converter reactive current (diode rectifier is disconnected). The figure shows current and voltages when active damping is disabled (black) and enabled (red).

Case No.4: Damping of oscillations caused by other harmonic sources (measurements)

The final case illustrates the effect of the active damping when the converter delivers reactive current while at the same time a diode rectifier is connected directly to the same bus as the PWM converter (as shown in Figure 12).

The reactive current reference of the PWM converter is set to $21A_{peak}$ (refernce for current $i_{measure}$ in Figure 12). The diode rectifier was connected and the active damping disabled. The resulting current and voltage waveforms are seen in Figure 14 (a). The voltage is distorted (THD 6.4%). The effect of enabling the active damping is seen in Figure 14 (b). The voltage distortion is clearly reduced. FFT analysis shows that the voltage total harmonic distortion (THD) is reduced from 6.4 % to 3.3%.



(a) (b)

Figure 14 Measured transformer current (i_{transf}) (red) and phase voltage at bus A (black) when the diode rectifier and the filter capacitor were connected. The PWM converter was running with active damping disabled (a) and enabled (b). The reactive current reference was $21A_{peak}$.

Comments

The controller parameters used in the presented simulations and during the measurements on the laboratory set-up have not been optimised for any specific application. It is therefore expected that the performance can be improved. A possible improvement may be to use other methods of error amplification in the active damping control loop. This has however not yet been found necessary.

The presented method for oscillation damping implies that the current reference signal is modified by a small amount (ref. Figure 8 and Figure 11). It is not expected that the current rating of the converter need to be increased due to the implementation of the presented active damping method.

The active damping method does not require additional measurements in applications were filter inductor currents and filter capacitor voltages are already measured and used in the control circuit. Currents and voltages in all three phases were measured in the presented cases of this paper. This is however not required. Measurements in two phases are sufficient as regard the active damping method.

The presented method does not require any knowledge of the grid reactance. The method will work independent of changes in grid reactance. This makes the method applicable in systems were the grid reactance varies over a large range during operation. Such systems are also typically exposed for the type of oscillations focused in this paper. An offshore or ship installation is an example of a system were large variations in grid reactance are to be expected and where damping methods may be needed.

The bandwidth of active damping is limited by the bandwidth of the current control loop. The performance of the active damping is also highly influenced by delays in the active damping control loop. A fully digital implementation was not possible with the currently used microcontroller. Analogue circuitries were therefore used for the time critical tasks. The method will however soon be tested in a fully digital implementation were the time critical tasks are placed in a Field Programmable Grid Array (FPGA).

The cases shown in this paper are simulations and measurements were traditional pulse-width modulation are used (triangular signal, comparator, reference signal). This is however just a choice of convenience. The active damping method is applicable to other types of current controlled grid connected converter as well (e.g. tolerance band control).

Finally, it should be noted that the technical data for the simulated cases and for the laboratory set-up in this paper are somewhat different. The results of the different cases presented in this paper can therefore not be compared directly (The focus of this paper is to demonstrate that the active damping method works. The focus is not on simulation model verification).

Conclusions

The results presented demonstrate that the introduction of active damping is a possible measure for reduction of oscillations due to LC-filters of line connected current controlled PWM converters.

The selected examples of this paper are grid topologies that gave low resonance frequencies. The natural damping of the system was low and thus oscillations were poorly damped. The selected examples may be somewhat extreme. They are however considered to be realistic for some applications, and thus relevant for illustration purposes.

Simulations and measurements show that the method works as intended. If active damping is implemented, then the voltage quality at the point of connection is maintained in cases were filter oscillations is to be expected

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