TAMING THE POWER

ABB Review series

Beating oscillations

Advanced active damping methods in medium-voltage power converters control electrical oscillations

PETER AL HOKAYEM, SILVIA MASTELLONE, TOBIAS GEYER, NIKOLAOS OIKONOMOU, CHRISTIAN STULZ – Power conversion in the medium-voltage range faces the challenge of performing power exchanges between electrical grids and loads that are both becoming ever more complex. The task is further complicated by the presence of electrical oscillations. Advanced control methods are therefore required to enable high-quality power conversion and to provide smart ways of attenuating resonant system behaviors.

Title picture
How do control methods tackle the challenge of resonant behavior in medium-voltage power converters?

A key requirement for soft damping is to provide the underlying control method with information on the content of the current and voltage signals around the resonant frequency and to allow the controller to react to actively damp the electric oscillations.

Medium-voltage (MV) drives represent a core ABB business that relies heavily on advanced power electronics, electromagnetic components, cooling technologies and automatic control technology. With more than one- fifth of the global market share, ABB is a key player in the MV drive global market. MV drives are ubiquitous in industrial applications that range from pumps and fans to compressors and rolling mills.

Traditionally, MV drives were used to connect an electrical machine that drives a mechanical load to the grid. However, with the growth of renewable energy sources and advanced transmission systems control, situations in which MV power converters inject current into a power network are becoming increasingly common. These situations include some types of solar and wind power generation, regenerative braking in rail systems, interfaces between HVDC (high-voltage DC) and AC transmission systems, and FACTS (flexible alternating current transmission systems). Power electronic systems are used within these applications to ensure the produced waveform and its frequency content are suitable for injection.

MV drives in a nutshell

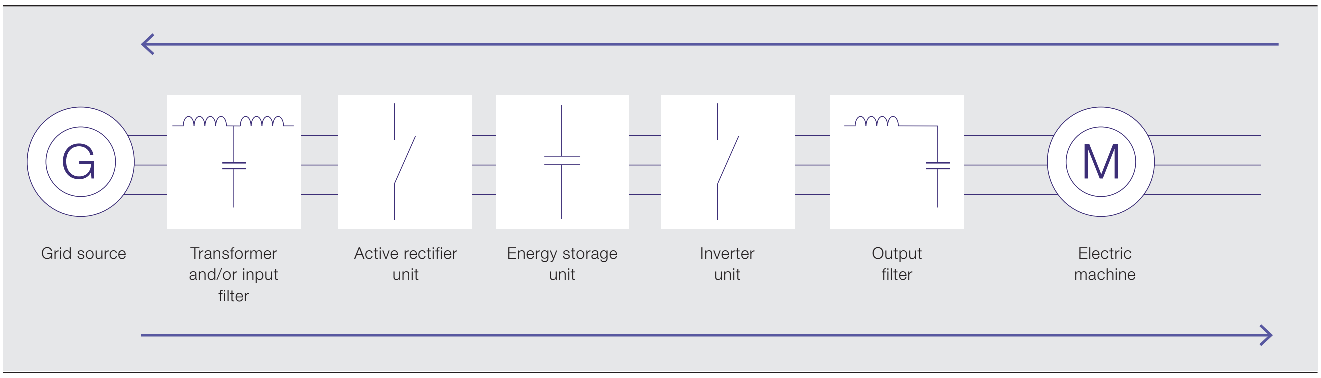
MV drives are power/frequency converters whose basic characteristics involve power flow and energy storage. Traditionally, the converter absorbs power from a three-phase AC power source (eg, the grid), stores this power as energy as DC using capacitors or inductors and then converts it back to AC – in a process called inversion – to drive an electric motor ➔ 1. This scheme can be reversed – when harvesting wind energy, for example, where the wind turbine converts mechanical movement to electrical power that is rectified and stored as DC before being fed back into the grid in an AC form.

The rise of harmonics

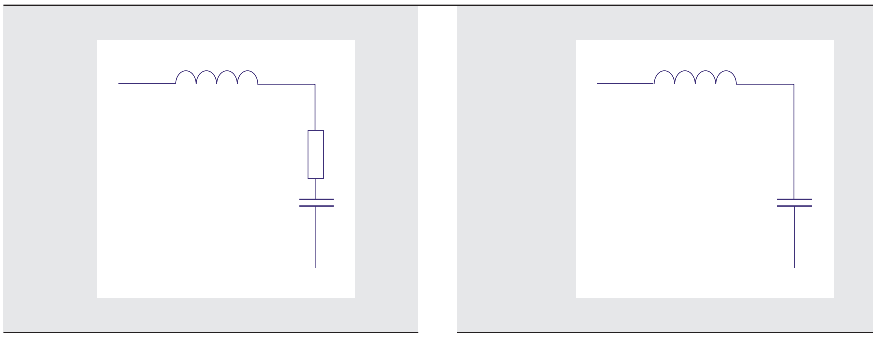
The power conversion processes of rectification and inversion are challenging. For example, since the actuation capabilities inside the converter are of a discrete nature, output voltage levels can only be generated in steps. This gives rise to electrical harmonics, which propagate through the system and are fed back to the grid or to the machine side.

A second, and equally important, challenge is presented by the inability to switch at high rates between the available voltage levels. Typically, switching frequencies range from several tens of Hertz to a few hundred Hertz. This is because the switching losses of the power converter – a major part of the overall losses of the drive – are proportionally related to the switching frequency.

1 MV drive with power flow arrows



2 The two main types of filter



2a RLC filter

2b LC filter

Lower frequencies cut operational costs and increase the overall system robustness, reliability and overall efficiency.

From the control point of view, this constrained range of switching frequency is extremely limiting.

Even more limiting is the relatively high level of low-order harmonics generated. Ideally, the voltage at the inputs and outputs of the MV drive would be purely sinusoidal. This, however, is an elusive goal. A more realistic objective is to minimize the harmonics that are superimposed on the fundamental signal. This translates into what are commonly referred to as grid codes, which impose restrictions on the individual harmonics (other than the fundamental) and their allowed magnitude. On the machine side, this is characterized by the total harmonic distortion (THD) of the current. The THD is essentially a measure of the collective strength of all the higher-order harmonics compared with the fundamental component.

Resonant filters

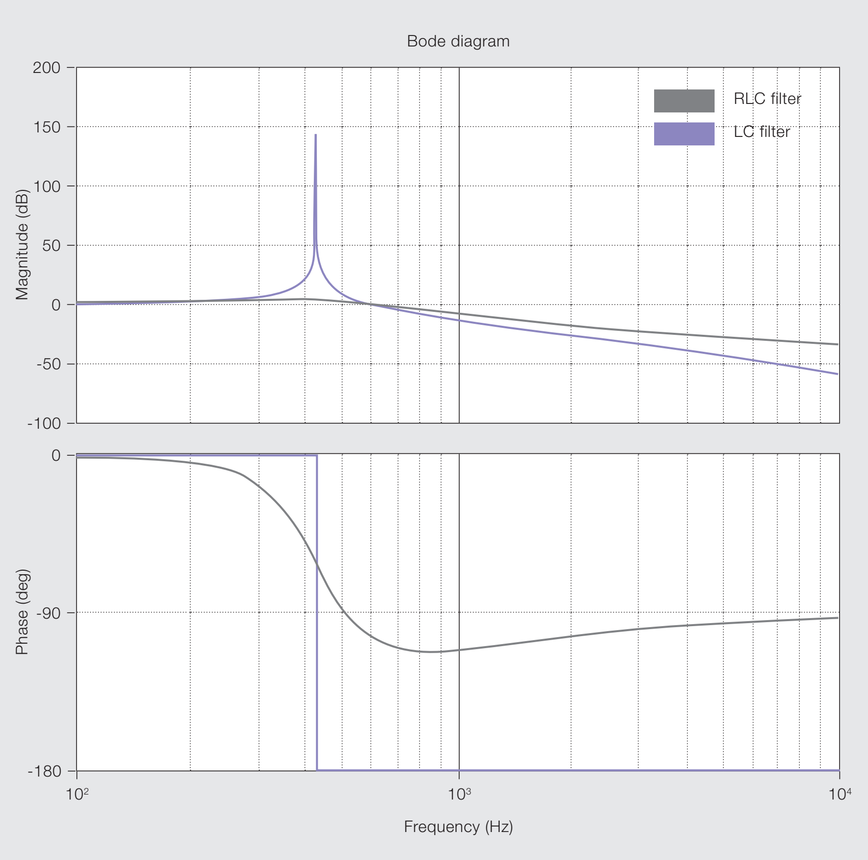
Hardware filters are often installed at the input and/or output of the MV drive in order to attenuate the effects of harmonics on the grid and/or the machine. Filters come in two main types: resonant (LC) or passively damped (RLC) → 2. Passively damped filters are attractive from the stability point of view as they do not amplify the low-frequency content of the signals and provide attenuation of the higher harmonics → 3. However, the resistive elements in the filter have high losses, which result in reduced efficiency of the overall power converter.

Two main questions arise from the control point of view: How to avoid generating harmonic content around the resonant peak of the LC filter; and if such harmonic content is present, how can it be attenuated?

The answer is provided by soft (or “active”) damping methods.

With the growth of renewable energy sources and advanced transmission system control, situations in which MV power converters inject current into a power network are becoming increasingly common.

3 Frequency response of an LC resonant filter and an LRC filter



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Soft damping methods

Soft damping methods pertain to smart techniques that attenuate the unwanted electrical oscillations of the system. These solutions incur no additional hardware costs at the system design level, but require a deep knowledge of the underlying system dynamics as well as expertise in control, estimation and optimization methods.

The discrete switched actuation levels that are intrinsic to a power converter result in harmonics of an infinite order – often referred to as switching ripple. These are present in all signals (voltages, currents, fluxes, torque, etc.) and may directly affect the control behavior. A key requirement for soft damping is to provide the underlying control method with information regarding the content of the current and voltage signals around the resonant frequency and to allow the controller to react to such information in order to actively dampen the electric oscillations. This requires very careful design of software filters (low-pass, bandpass, notch, etc.) and/or advanced estimators.

There is a plethora of methods – both in the academic and the industrial communities – to design controllers that attenuate resonances.

Single-input, single-output methods

The first attempts to tackle oscillations were mainly based on frequency-domain concepts and the shaping of the closed-loop system response. These attempts mainly used PID (proportional-integral-derivative) concepts for single-input, single-output (SISO) systems and relied on technical results – from the 1930s, 1940s and 1950s – regarding the design and tuning of parameters. This approach can be used in conjunction with available modulation and control schemes – for example, pulse-width modulation (PWM) [1] and direct torque control (DTC) [2]. However, there are many caveats: The underlying system is neither SISO nor continuous in nature. Instead, it exhibits very complex interaction dynamics between inputs and outputs.

> Ideally, the voltage at the inputs and outputs of the MV drive would be purely sinusoidal. This is an elusive goal. A more realistic objective is to minimize the harmonics that are superimposed on the fundamental signal.

Multiple-input, multiple-output methods

Multiple-input, multiple-output (MIMO) methods that utilize the state-space representation (also known as the time-domain approach), developed in the 1960s, along with linear quadratic regulator (LQR) control design together represent a major evolution in active damping methods.

MIMO methods capture the dynamics of the system in a single set of first-order differential equations and use this information to predict the system behavior over the future time instances and hence generate optimal corrective control actions that result in long-term positive effects on the attenuation of the unwanted oscillations. MIMO methods offer a more precise handle on the complex interactions inside the system and their effects on the resonances than do the SISO-based methods that preceded it. MIMO-based design still retains the caveat of assuming that all the signals in the system are continuous in nature and it ignores the switching effect mentioned earlier.

The LQR approach, which generates the changes in the reference signals needed to attenuate the unwanted oscillations, has been used in two different control approaches as an outer loop: Model predictive direct current control (MPDCC) for the grid side and model predictive pulse pattern control (MP^{3}C) for the machine side [3].

Advanced time and frequency methods

Although extremely effective, MIMO- and LQR-based active damping control schemes still suffer from the fact that they only manipulate the reference signals in order to achieve the attenuation of the electric oscillations. More advanced techniques for attenuating oscillations use optimized pulse patterns (OPPs). The OPPs are usually designed in such a way that the harmonic content at the resonant frequency is eliminated. However, disturbances or slight changes in the switch positions may reintroduce this unwanted harmonic content, which is, in turn, magnified by the resonance peak of the physical filters. As such, it is more effective to look at each switching action in the system and analyze its effect on the attenuation or creation of harmonic content at the resonance peak.

This analytical information on the harmonic consequences of control actions is invaluable when making the following decision: Should the switch happen as planned, or should it be shifted so that it can help dampen the resonance? Such advanced methods require extremely low ratios between the resonance frequency of the hardware filter and the actuation/switching frequency. As such, the performance of the system can be pushed to a higher level and the size of the passive elements in the system, and consequently the cost, can be reduced.

The vision

A control engineer at ABB has nowadays a very effective and well-studied arsenal of methods for achieving active damping of electrical resonances. However, this is by no means the last word on the subject. With the presence of resonant circuits both at the load and at the source, as well as in the intervening subsystems, systems are becoming more and more complex. Control methods developed in the last century have provided the solution to the active damping problem for single power conversion systems, but the evolution of power conversion systems and the expansion from single- to multiple-system setups makes further research necessary. The challenges in future power conversion systems stem from scalability in scope and complexity, as well as practical aspects such as communication delays between the subsystems and computational constraints imposed by the control hardware platforms.

When it comes to attenuating resonances, it may well be that it is more effective to look at power conversion systems as a whole and design control methods that exploit the total system structure rather than the individual subparts. This will lead to optimized system design, cost reduction and better efficiency.

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