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doi:10.15199/48.2015.11.32

Reaction of grid-connected converters to unsymmetrical grid voltages with focus on modular multilevel converters

Abstract — The topology and the resulting properties of power-electronic converters influence mitigation concepts for undesirable power oscillations in the connected assets. Power theory in general provides an answer for the optimal way to operate under aspects of efficient energy transmission. However, practical aspects and design considerations (including size and cost) as well as grid-code specifications also influence the chosen technical solution. With this background, control objectives have to be related to the technical options available and the demands given by e.g. grid codes. One aspect frequently discussed is the mitigation of power fluctuations with double line frequency resulting from unsymmetrical AC-grid voltages. In case of conventional voltage- and current-source-based converters, where the converter itself does not contain any energy storage, these power fluctuations affect the DCside. This paper concentrates on the special case of modular multilevel converters (MMC) where the converter itself contains relevant energy-storage devices. For this appli-cation, a control structure is described which incorporates the optimal coupling between ACside and DCside also under unsymmetrical AC-grid voltages and smoothly transits from symmetrical to unsymmetrical conditions.

Streszczenie. *Topologia i wynikające z niej właściwości przekształtników energoelektronicznych oddziałują na koncepcje ograniczania niepożądanych oscylacji w sieciach rozdzielczych. Teoria mocy dostarcza ogólnie odpowiedzi odnośnie pracy systemu, z punktu widzenia skutecznej transmisji energii. Aspekty praktyczne oraz warunki projektowe (wliczając w to rozmiary i koszt) jak również standardy sieciowe, mają także wpływ na rozwiązania techniczne. Mając powyższe na uwadze, cele sterowania muszą być związane z dostępnymi możliwościami technicznymi i wymaganiami standardów sieciowych. Jednym, często dyskutowanym problemem jest ograniczanie zmienności mocy z podwójną częstotliwością sieci, spowodowanej asymetrią napięcia. W przypadku przekształtników konwencjonalnych ze źródłem napięciowym lub źródłem prądowym, nie mających żadnych źródeł energii, ta zmienność mocy oddziałuje na stronę prądu stałego przekształtnika. Artykuł skupia się na szczególnych przypadkach modularnych wielopoziomowych przekształtników (MMC) mających odpowiednie zasobniki energii. W artykule przedstawiona jest struktura sterowania takich przekształtników, która zawiera optymalne sprzężenie między stroną prądu zmiennego i stroną prądu stałego przekształtnika, działająca również w warunkach asymetrii napięć w sieci prądu zmiennego i łatwo przechodząca z warunków zasilania symetrycznego do asymetrycznego.* ***Reakcja zasilanych z sieci przekształtników na asymetrię napięcia ze szczególnym uwzględnieniem modularnych przekształtników wielopoziomowych***

Keywords — modular multilevel converters, unsymmetrical grid voltages, mitigation of power fluctuation.
Słowa kluczowe: Modularne przekształtniki wielopoziomowe, asymetria napięciowa, redukcja zmienności mocy.

I. Introduction

This paper considers a three-phase AC bus connected to a DC bus via a partly idealized converter: the switching frequency is supposed to be infinite, while the energy-storage capability of the converter itself is zero. Under symmetrical grid voltages, the powers at the AC bus and the DC bus are identical at all time instants and both constant – representing well-known optimal steady-state conditions. Unsymmetrical grid voltages on the AC bus at purely active power relate to a power fluctuation with twice the fundamental frequency (second-order-harmonic fluctuation) [1, 2]. On the DC-bus side of the converter, constant power remains the optimal choice from the point of view of power theory. Obviously, the optimal way to operate the two busses is – with regard to energy transfer rated by power theory – different. In case of converters without internal energy storage, it is not possible to meet both demands at the same time. Even if the DC bus contains a smoothing capacitor, DC-voltage fluctuation remains unavoidable. Solutions to this problem are widely discussed. [3 – 5] represent a small selection out of many papers related to this subject.

The extreme case of unbalance is reached in case of faults where the grid voltages become single phase and, in this way, are identical to single-phase applications for lower-power devices and AC-railway applications. In case of railway applications at 16.7 Hz, resonant filter circuits tuned to about 33.4 Hz are regularly employed, while at 50 Hz mostly only a DC smoothing capacitor is applied. Low-power applications use a variety of technologies to mitigate the second-order power fluctuation.

For high-power grid-connected converters (e.g. high-voltage DC transmission, HVDC) at 3-phase AC, such filters are not applicable because of cost, size and because the unsymmetrical voltage is not a typical point of operation. However, in many cases the converter has to continue to operate (“Fault Ride Through”) and react properly to the unsymmetrical AC grid. For infeed converters (e.g. photovoltaics and wind-energy turbines, but also HVDC transmission), grid codes define the desired reaction.

Consequently, a control scheme is desirable which allows to tune the reaction of the controlled converter to the demands of the grid code taking into account the physical limitations imposed by the converter and its properties. Within this paper, first, a more detailed comparison of converter topologies and their inherent possibilities and limitations is given. In the following, MMC converters [7 – 8] are focused where energy storage is inherent to the converter topology itself. For these, a control scheme is introduced which clearly separates converter-near control and asset characteristics. In this way, a modification of the asset characteristic on the basis of assumed grid-code demands modifies the reaction of the converter, while the converter-near control is unchanged. This approach leads to a high-quality control scheme [9] supporting various ways to react to unsymmetrical voltages without modification of the fast and stable converter-near control. In case of a MMC it is even possible to deliver energy in an optimal way at both AC- and DC-bus sides while pushing the power oscillation into the link capacitors and/or circular currents of the MMC. In contrast to e.g. [10], [11], no modification of the converter-near control is needed for this adaption.

II. Examplary Converter Topologies and their Properties

The most common converter used is the three-phase two-level converter (Fig. 1). The converter itself (solid box) does not contain any energy storage. Consequently, instantaneous power on both sides is always identical. Thus, oscillations cannot be eliminated by the converter alone. If the DC capacitor is included (dotted extension of box), oscillations will be smoothed by the DC capacitor – but not eliminated. For full elimination, a tuned filter (as, e.g., in the mentioned railway applications) would be needed.

However, such filters also modify the reaction to load dynamics and, consequently, the layout and parameterization of the control. Control schemes forcing constant power on the AC bus under unsymmetrical conditions cause nonactive power and are not feasible at single-phase operation (100% unbalance).

For HVDC transmission and high-power short-distance AC-grid coupling, modular multilevel converters (MMC) are used more and more frequently. Their structure can be seen in Fig. 2.

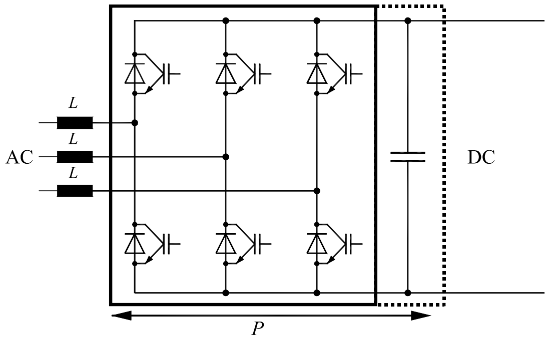

Fig. 1. Three-phase two-level converter

With regard to the mitigation of power oscillations, two major differences are observed: On the one hand, each submodule of each converter arm contains its own DC-link capacitor. On the other hand, arm inductors decouple the converters placed in the arms of the MMC with respect to their voltage. Two consequences result: With respect to the AC and the DC bus, the converter now contains energy-storage capability, mainly in the capacitors, less in the arm inductors.

Furthermore, circular currents can be implemented to transfer energy from arm to arm within the converter – without modifying voltages or currents at the busses connected to the converter [8]. These options can be used by the converter control to eliminate power oscillations as demanded by the grid codes for AC and DC.

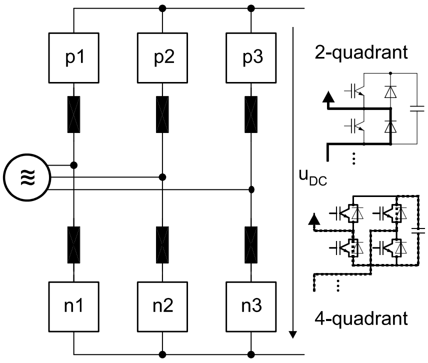

Fig. 2. MMC: 2-quadrant and 4-quadrant topology

III. Control Structure

The selected control structure is shown in Fig. 3, [9]. It is advantageous for controlling power-electronic devices connected to the grid because it separates and, at the same time, integrates two main control perspectives:

- The frequency-domain section contains the asset characteristics as well as a feed-forward control based on a model of the power-electronics device. Adaption to e.g. grid codes is done by a modification of the asset characteristics.
- The multi-variable time-domain control section implements the converter-near control including protection of the power-electronic devices against, e.g., overcurrent.

It is self-evident that the implementation of the asset characteristics and the feed-forward control has to honor the physical and technical limitations of the attached power-electronic devices. However, protection and fast dynamic reaction including suppression of a part of the disturbances is independently taken care of by the time-domain multivariable control.

To reach these goals the control is divided into an outer control loop (high-level controls) and a subordinated inner control loop (low-level controls).

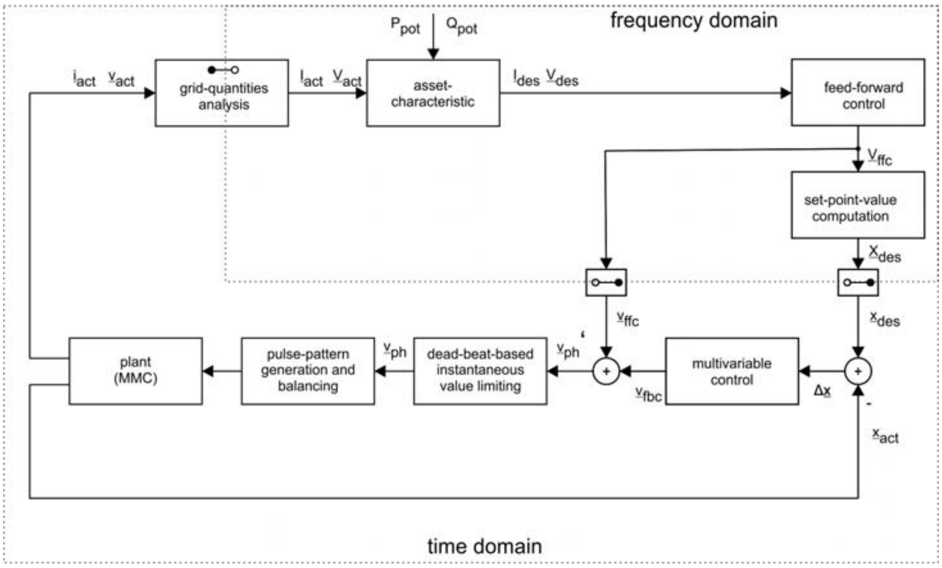

Fig. 3. Multivariable control structure comprising frequency-domain and time-domain sections

The outer control loop is implemented in frequency domain, processes the actual (measured) grid quantities (i_{act}, v_{act}) and determines corresponding set points (i_{des}, v_{des}) for the inner control loop. The outer control loop reacts within a few grid periods. In normal operation, the outer control loop has to follow the set points (P_{pot}, Q_{pot}) provided by the dispatch unit. However, under fault conditions, the outer control adapts these set points automatically based on the measured AC and DC quantities, in order to achieve a new stable operating point. This adaption is performed by the asset characteristic implemented within the outer control loop, cf. Fig. 3.

One relevant advantage of these asset characteristics is that they completely define the behavior of the system as a whole under all conditions which are not "instantaneous reaction to faults" – in case of the control used here, the instantaneous reaction to faults carried out by the inner control loop takes about 10 ms to 15 ms even in case of DC short-circuit mitigation, cf. Fig. 4 and Fig. 5. In this way all characteristics relevant for e.g. multiterminal operation are contained in the asset characteristics, allowing multi-vendor assets to participate in a multiterminal system without the need to publish vendor-specific inner control loop implementations.

The starting block of the inner control loop is a feed-forward block (based on a model of the asset). It pre-calculates the expected stationary quantities. The predicted arm-voltage set-point values are given to the instantaneous-value-limiting block directly. As input to the multivariable control, additional set-point values for e.g. the module-capacitor voltages and arm currents are calculated.

The multivariable control is challenging: The six arm voltages have to be adjusted such that all control objectives are met. This includes AC-side currents, DC-side currents, circular currents within the converter and the module-capacitor voltages. These have to be symmetrized – having in mind that they are not constant but oscillate due to the single-phase operation of the associated converters modules. Based on its control rules the multivariable control optimizes the pre-controlled set-point-values for the arm voltages.

The instantaneous converter-arm currents are observed and if necessary limited to the admissible value by deadbeat control, which passes the final set-point values to the pulse-pattern generator. The challenging inner control is generally vendor-specific and subject to intellectual property. For this reason, the interface between outer and inner control is solely based on physical quantities, namely voltages and currents at the terminals of the converter. In this way, the above-mentioned anti-discriminatory multi-vendor properties are reached.

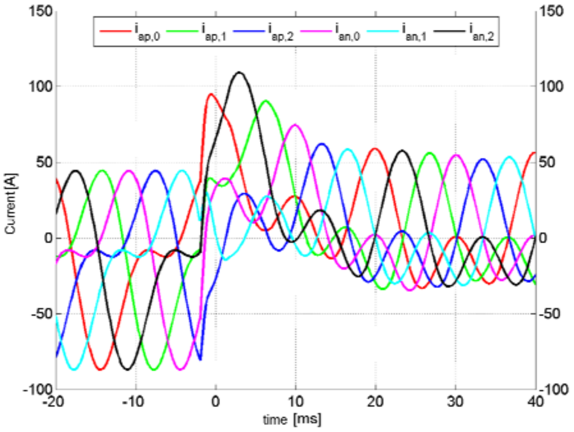

Fig. 4. Dynamic reaction of MMC to DC fault – Simulation results

IV. Verification of The Simulation

The following section on simulation results utilizes a simulation of a high-voltage modular multilevel converter. To verify the simulation carried out with the simulation tool VIAvento [12], low-voltage experiments have been carried out. The following two figures cf. Fig. 4, Fig. 5) show the reaction of such a low-voltage (600-V-DC voltage) MMC to a DC-side short circuit – comparing its arm currents ("ap" for the upper arms "positive" and "an" for the lower arms "negative"; count is 0 to 2 for the three branches) to these predicted by simulation. It can be seen that the results match excellently during steady state and are very close during dynamics. Also, the smooth transition between steady-state, dynamics and new steady-state conditions predicted by the simulation and the discussion of the control structure in the previous section is verified by the experiment. More detailed results concerning short-circuit mitigation are found, e.g., in [13].

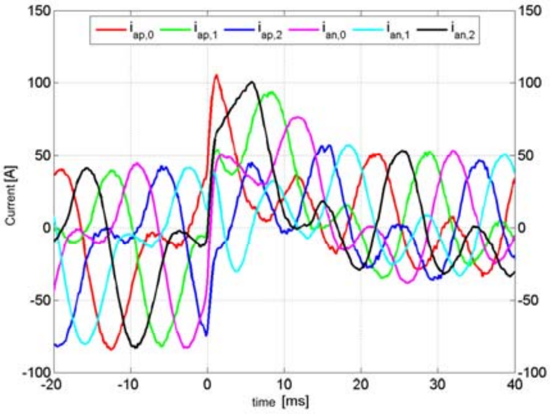

Fig. 5. Dynamic reaction of MMC to DC fault – Measurements

V. Simulation Scenario and Simulation Results

The simulation scenario bases on a MMC with four-quadrant modules as already shown in Fig. 2. It feeds from an AC grid into a DC grid. The parameters used for this simulation match an HVDC application operating at a total DC voltage of 800 kV with a DC current of about 600 A. All currents are counted positive from converter towards grid (on AC and DC side). The AC voltages are defined conductor to neutral, the DC voltage is defined plus to minus. The connection to the AC grid is via a grid impedance – consequently, the instantaneous transition from three-phase symmetrical to two-phase unsymmetrical operation on the AC grid translates to the AC-side voltages of the MMC via the reaction of the asset characteristic without causing extreme currents. The voltage transition is the basis for the whole scenario and seen in Fig. 6.

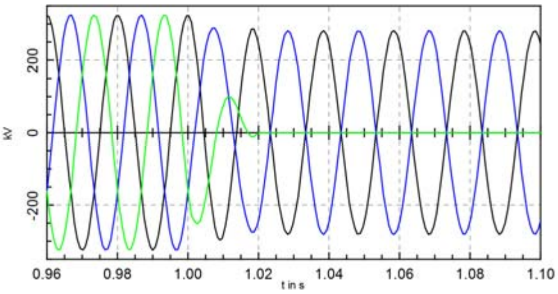

Fig. 6. AC-side voltages of the MMC; transition from symmetrical to unsymmetrical grid conditions at $t = 1$ s

At t = 1 s, the phase voltage of conductor 0 is set to zero, creating a single-phase system with three conductors. The dynamic reaction of the converter takes about one period (20 ms) to reach the new steady-state conditions.

For demonstration and to receive illustrative figures, the asset characteristic is set such that the active power remains constant and no negative-sequence current components are generated, the current remains purely positive sequence. This is certainly not the optimal approach – in "real world" applications, a reduction of active power and an injection of reactive current to support the grid might be more adequate. An implementation of such a behavior requires a straightforward modification of the asset characteristic. With the chosen demonstrative strategy, the AC-side currents increase (cf. Fig. 7).

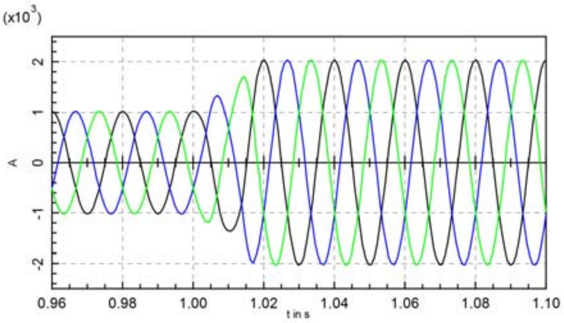

Fig. 7. AC-side currents of the MMC; transition from symmetrical to unsymmetrical grid conditions at *t* = 1 s

For the DC-side, the asset characteristic is set to constant voltage operation (cf. Fig. 8).

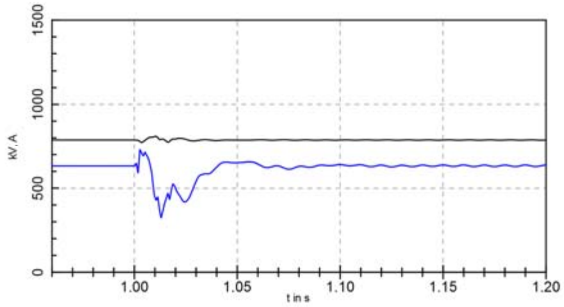

Fig. 8. DC-side voltage and current of the MMC converter DC voltage: black; DC current: blue, larger variation

The DC side is coupled with a constant- voltage grid of 800 kV with a resistance of just 5 Ω and an inductance of only 2 mH – consequently, the DC current reacts sensitively to DC-voltage variations. This explains the transition (about 20 ms for the major part of the dynamics, 50 ms to steady-state) of the DC current depicted in Fig. 8.

The instantaneous power on the AC side of the MMC is shown in Fig. 9.

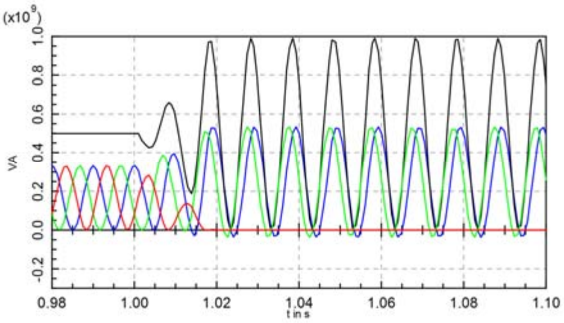

Fig. 9. Time function of instantaneous powers on the AC side red, green, blue: associated with the three conductors black: total instantaneous power

Up to t = 1 s, the instantaneous powers associated with the three conductors (red, green, blue) add up to the constant total instantaneous power on the AC side (black). With the voltage transition to zero and the single-phase characteristic of the grid voltages one of the three AC-side powers goes to zero, the other two add up to the now oscillating total instantaneous power of the converter – which keeps the original mean value because active power is kept constant by the control. Normally, this power fluctuation would be seen on the DC side.

The asset characteristic is, however, set to constant power on the DC side and, consequently, uses the ability of the MMC arm modules to act as energy-storage elements. This is realized by suitable variation of the arm currents and arm voltages as depicted in Fig. 10 and Fig. 11.

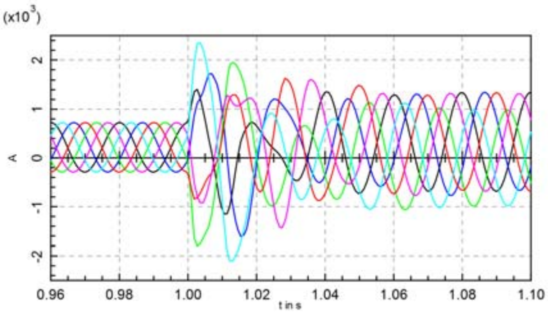

Fig. 10. Arm currents of the MMC

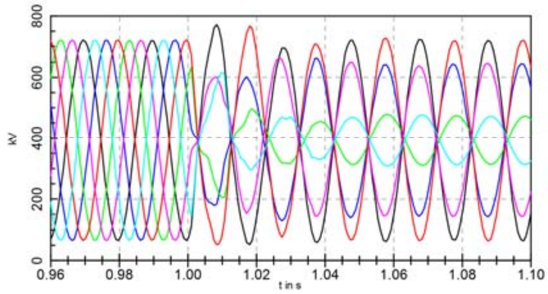

Fig. 11. Total arm voltages (Cumulated voltages of all modules per arm)

It can be seen that the steady-state time functions under unsymmetrical grid conditions are still symmetrical in many ways, but much more complex than with symmetrical grid conditions. The Figures 6, 7, 8 and 9, showing the AC- and DC-side quantities of the MMC converter, prove that these arm currents and total arm voltages actually result in the pre-defined characteristics of the converter.

Energy has to be stored and fluctuate within the converter – and this happens in the capacitors of the modules as seen in Fig. 2. Fig. 12 shows the cumulated voltages of the capacitors of each arm.

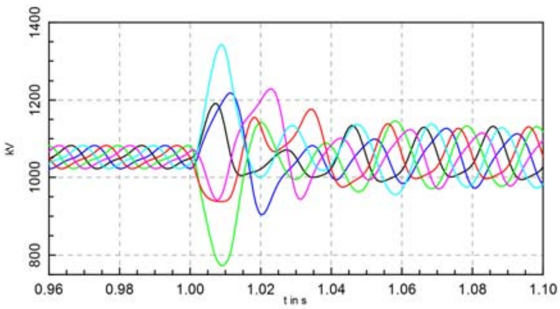

Fig. 12. Total module capacitor voltages (Cumulated voltages of all module capacitors per arm)

As expected, the relatively narrow band of module-voltage variation expected under symmetrical operation of the MMC is spread considerably, and the voltage variation is no longer identical for all modules. However, the effect is not as large as expected and additional measures as circulating currents are not yet used. A mitigation and even full suppression of AC-side unbalance to the DC side of the MMC is viable with a relatively small effect on the rating of the capacitors of the MMC. Of course the additional rating of the capacitors strongly depends on the boundary conditions set for the operation – and the evaluation of such ratings is complicated because the oscillation of the capacitor voltages strongly depends on the point of operation and is also influenced by reactive current components. This would not be the case for usual grid-connected converters as seen in Fig. 1.

VI. Conclusion

This paper discusses the options for converter operation at unsymmetrical grid voltages with special attention to modular multilevel converters (MMC).

The functionality of the simulation tool VIAvento is demonstrated by a comparison between measurement and simulation results at a test bench. The simulation then analyses the dynamic reaction of a suitably controlled MMC to the AC grid unbalance. One phase voltage is set to zero, leading to single-phase conditions.

Oscillating instantaneous power on the AC side and quasi-constant voltage and current on the DC side verify that the MMC is able to dynamically adapt to the unbalance and provide the needed power fluctuation.

Internal quantities of the MMC further illustrate the way in which the objective is reached. An analysis of the cumulated module-capacitor voltages of the MMC arms shows the additional voltage variation resulting from the power fluctuation – but even in this severe case the fluctuation is not extreme.

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