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Impact of Current Limitation of Grid-forming Voltage Source Converters on Power System Stability

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Abstract: Grid-forming voltage source converters (VSC) have important characteristics of synchronous generators (SG). These include the provision of inertia and, in particular, voltage source behavior. These properties are required to make interconnected power systems with up to 100 % converter based generation possible. However, grid-forming VSC can not replace an important feature of SG: overcurrent capability. This property of SG contributes to power system stability. In the case of severe disturbances, SG may initially be overloaded before the load is gradually shared with other feed-ins. Due to the risk of damage, VSC have an overcurrent protection. However, most grid-forming VSC control concepts do not incorporate a sophisticated overcurrent limitation. This paper shows, by means of simulations, that current limiting of grid-forming VSC can lead to significant power system stability issues due to unsuccessful load sharing between other feed-ins. In addition, the paper shows, that with an increasing share of constant power loads, these issues can occur sooner.

Keywords: Power system stability, voltage source converter, current limitation

1. INTRODUCTION

Current-controlled VSC of renewable energy sources (RES), storage systems and high-voltage direct current (HVDC) transmission systems do not contribute to small-signal stability of power systems. These VSC rely on a connection to an external grid characterized by a sufficiently stiff grid voltage. The basic control objectives behind current-controlled VSC are twofold. First, the energy storage in the DC-capacitance of converter-based feed-ins is typically small due to monetary reasons. In order to keep the DC voltage within tolerable limits, a fast power control on the VSC side is needed. The second objective is the protection against overcurrents, which would destroy the power electronics. Changes in grid voltage can be compensated within fractions of seconds, therefore the name grid-following VSC. Both mentioned control objectives are achieved by means of fast current control, de facto resulting in current source behavior. In contrast to SG, they do not contribute to power system inertia intrinsically. As a consequence, higher rates of change of frequency (RoCoF) and other undesired effects are to be expected in case of high shares of converter based generation (ENTSO-E, 2017; Schöll et al., 2018). In fact, above a certain share of current-controlled VSC, power system stability is at risk, so that the share of converter-based generation is limited in some countries, e.g. Ireland (PPA Energy (2013)). The introduction of new ancillary services like the provision of reactive power in case of short-circuits or emulating the dynamic behavior of SG by means of current-controlled VSC (Chen et al. (2011)) can only mitigate this problem, but not solve it entirely (Duckwitz and Fischer (2017)). In current power systems, dynamic properties of SG play a key role in ensuring stability: They behave as voltage sources that provide inertia intrinsically.

While there are examples of successful operation of 100 % converter based power systems, these systems are small islands in which a single VSC provides a fixed reference voltage. As a consequence, the VSC is responsible to deal with all disturbances in the system. Parallel operation of several VSC with such an operational concept is not feasible, which is why it cannot be used in interconnected power systems.

Grid-forming VSC are a possible solution for interconnected power systems with up to 100 % converter feed-in via HVDC and RES. Their control concept attempts to emulate the voltage source behavior of SG and, thus, enables parallel operation of VSC. Unlike grid-following VSC, grid-forming VSC usually adjust the setpoints for the voltage phase angle and amplitude according to a given control concept and do not control the resulting currents directly. While the dynamic behavior of SG is predetermined by its physical properties, the dynamic behavior of VSC in the time scale of interest only depends on their control concept, opening a wide range of possible implementations. This is why a range of different grid-forming control concepts has been developed (Duckwitz, 2019; Weise and Korai, 2019).

The control concepts differ with respect to their dynamic behavior and the way how synchronization with the grid is achieved. However, most concepts do not incorporate a sophisticated and integrated approach to limit currents. As mentioned above, the power electronics of VSC must be protected against overcurrents. While the implementation of current limitation is straightforward for VSC with fast current control, this is not true for grid-forming VSC. In fact, in order to contribute to small signal stability by behaving as a voltage source with inertia, the current must not be controlled fast but be free to react to the requirements of the power system. Only if the limitations of the VSC are reached, the VSC should deviate from its voltage source behavior in order to keep the current within the tolerable range.

Independent of the implementation chosen for current limitation, it is clear that current limitation will have an impact on the behavior of the power system. This is true in particular if there are only few or even no SG connected to the system. Hence, current limitation of grid-forming VSC must be considered appropriately when simulating the dynamic behavior of interconnected power systems in case of power imbalances. Otherwise, fundamental effects of current limitation on power system stability will be neglected, which could lead to invalid results of stability studies. Many simulation studies regarding the dynamic behavior of grid-forming VSC are limited to the investigation within permissible current limits or of single units connected to a stiff grid voltage under synthetic voltage and frequency disturbances. Other studies are investigating the influence of current limitation and are also finding stability problems, but often the grid-forming concepts used are still based on lower-level current control concepts resulting in a current source behavior (Paquette and Divan, 2013; Xin et al., 2016). As these leave the question on the impact of current limitation of grid-forming VSC with voltage source behavior on power system stability unanswered, we investigate possible effects using a simplified grid and MMC model with a heuristic current limitation concept in this paper. First, a simplified Modular Multilevel Converter (MMC) model is introduced as a popular technology for VSC. After that, we present the corresponding grid-forming VSC control concept and a heuristic current limitation approach. Then the transient behavior and effects of MMC current limitation on power system stability will be analyzed based on a simple grid model.

2. GRID-FORMING MODULAR MULTILEVEL CONVERTER

Fig. 1 shows an overview of the control setup used in this paper. The MMC is connected to the AC-grid via an impedance. For simplicity reasons, the DC-side is represented by an infinite DC-source, hence the DC-Voltage is constant. The MMC is represented by an average value model, which is essentially a voltage source generating a 3-phase voltage according to the number of active submodules according to $\hat{N}_{\mathrm{abc}}$. For this purpose, the voltage $\tilde{u}_{\mathrm{abc}}$ at the point of common coupling (PCC) and the MMC currents $\tilde{i}_{\mathrm{abc}}$ are used in the MMC control setup. Each element of this control setup is described in the following subsections.

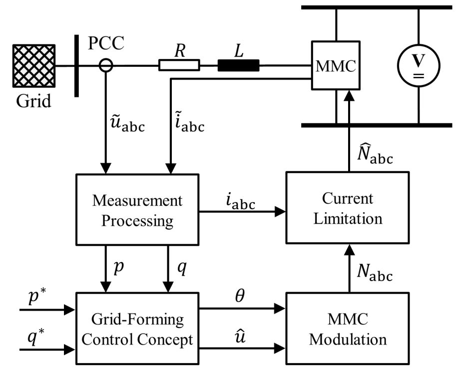

Fig. 1. Overview of the MMC grid-forming control setup.

2.1 Measurement Processing

The measurement of grid voltage $\tilde{u}_{\mathrm{abc}}$ at the point of common coupling (PCC) and the measurement of MMC currents $\tilde{i}_{\mathrm{abc}}$ are delayed by means of first order lags. These values are used to calculate VSC active power p and reactive power q. In this paper, the time constants of the first order lags for the measurement of currents and voltages are set to 100 µs and for power measurements to 4 ms.

2.2 Grid-forming Control Concept

Grid-forming control principles commonly found in literature are based on power and differ in their dynamics between the power inputs p and q and the outputs voltage phase angle θ and voltage amplitude $\hat{u}$. The difference between the grid and VSC voltage phase angle is used to control active power output. The VSC reactive power output is controlled according to the difference between the grid and VSC voltage amplitude.

One way to achieve a grid-forming behavior is to implement a dynamic model of SG, which is well-known as the virtual synchronous machine (VSM) (Wrede and Winter (2017)). Fig. 2 (a) shows a possible active power part of a VSM. Similar to the dynamic behavior of SG, the difference between active power setpoint and actual output is interpreted as an acceleration $\ddot{\theta}$ of a virtual flywheel. The control concept shown also has a frequency droop characterized by the constant K_P based on the frequency deviation $\Delta\omega$ providing frequency containment reserve. The acceleration of the virtual flywheel is limited according to the factor K_θ analogous to the acceleration time constant of SG. According to

$$\omega = \int \ddot{\theta}\,\mathrm{d}t + \omega_0 \quad \text{and} \quad \theta = \int \omega\,\mathrm{d}t + \theta_0 \tag{1}$$

the VSC frequency ω and phase angle θ are determined. Changes in the VSC active power output result in an acceleration or deceleration of the virtual flywheel and thus the VSC voltage phasor corresponding to the behavior of inertia of SG.

Analogously, Fig. 2 (b) shows a possible reactive power part of a VSM. The difference between reactive power setpoint and output is interpreted as the rate of change of the VSM voltage amplitude $\hat{u}$ according to the factor K_U analogous to the excitation time constant of SG.

The reactive power part also includes a voltage droop characterized by the constant K_Q which is based on the internal voltage deviation similar to the active power part.

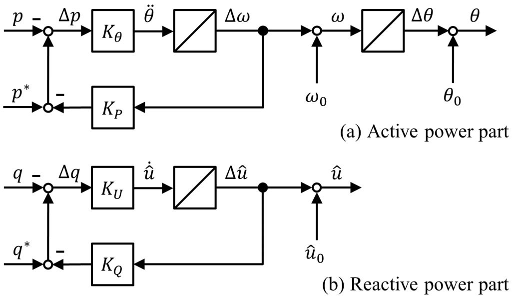

Fig. 2. Virtual synchronous machine grid-forming control concept.

2.3 Modular Multilevel Converter Modulation

According to the grid-forming control concept setpoints for the VSC voltage amplitude $\hat{u}$ and phase angle θ, the number of inserted MMC submodules (SM) N_{abc} is calculated. First, a three phase voltage signal

$$\mathrm{e}_{\mathrm{abc}} = \hat{u}\sin(\theta + \theta_0 + \theta_{\mathrm{abc}}) \qquad (2)$$

is calculated. The voltage signals are phase shifted by 120° to each other, which is achieved by means of the term θ_{abc}. Afterwards, each voltage signal is discretized using the available SM using nearest level modulation (NLM) (Wang et al. (2018)), resulting in the number of active SM $N_{\mathrm{abc}} = \{N_{\mathrm{a}}\, N_{\mathrm{b}}\, N_{\mathrm{c}}\}$ for each phase.

2.4 Current Limitation

The repercussions of the current limitation on power system stability should be investigated in a simplified way. To this end, VSC current limitation in this paper is based on heuristic control approach. In this approach, VSC currents are not limited in the sense of a sinusoidal current with maximum amplitude. Instead, the VSC currents are clipped above a maximum current in order to maximize the VSC active and reactive power output during times of current limitation. This is done for each phase separately by successivly switching on and off a certain amount of SM. The method for VSC current limitation used in this paper is shown in Fig. 3 (a). The first step is to measure the actual VSC currents of a certain phase in every evaluation step k. If the current $|i|$ is above the first threshold $i_{\mathrm{th1}} < i_{\mathrm{max}}$, the number of switched-on SM N^k determined by the NLM is reduced by ΔN^k resulting in the final value of switched-on SM $\hat{N}^k$. The number of SM to be switched off ρ must be chosen in every evaluation step, so that the gradient of current just changes its sign. This ensures that the current stays within the tolerable range. Alternativly, if the current passes the first threshold, a second threshold with $i_{\mathrm{th2}} < i_{\mathrm{th1}} < i_{\mathrm{max}}$ is used. In this case the current is either increasing but does not have to be limited yet, or the current drops again after it has been limited and the current limitation can be reduced again. Hence, if the current $|i|$ is below threshold i_{th2}, the number of switched-off SM can be incrementally reduced. This gurantees, that the VSC leaves current limitation mode. If the current is between the two threshold values, the number of reduced SM of the last evaluation step k-1 is used. Fig. 3 (b) shows an example of how the heuristic works based on a time segment when the current limit is reached. The described current limitation heuristic does not hinder the grid-forming capabilty, since the currents are not controlled directly and voltage source behavior is maintained.

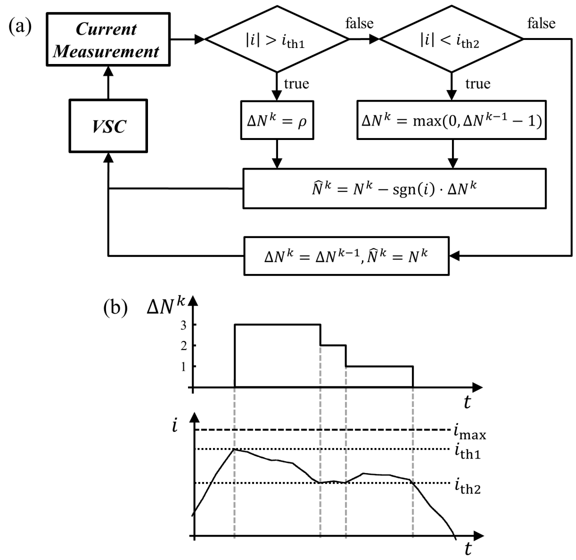

Fig. 3. Simplified flowchart of the heuristic current limitation and illustrative example.

The simulation results in Fig. 4 illustrate the behavior of the described current limitation heuristic for a load step at the PCC of a current limited grid-forming VSC. Due to the load step at $t = 0\,\mathrm{s}$, VSC active power output rises abruptly and the grid voltage slightly decreases. As described, current limitation is achieved by means of reduction of VSC phase voltage, leading to an additional slight grid voltage decrease. It should be mentioned that the current limitation concept presented produces strong harmonics in the short term, which were not considered in the subsequent studies. It should also be noted that the heuristic shown is not suitable for a real implementation, but only for dynamic simulations of interconnected power systems.

3. SIMULATION RESULTS AND DISCUSSION

In order to show the impact of current limiting of grid-forming VSC in parallel operation on power system stability, a simple grid with three nodes connected by two lines is used, see Fig. 5. The focus of the simulative investigations is to show fundamental effects on power system stability. However, parameters of the grid are chosen so that they are representative for a 20 kV distribution grid. Each line of the grid has identical line parameters: AC-resistance $R_l = 1\,\Omega$ and reactance $X_l = 10\,\Omega$. One MMC and one load are connected to each node. Apparant power of each MMC is $S = 15\,\mathrm{MVA}$ and all have 25 SM in each arm. All MMC have identical parameters, see table 1.

At the beginning of each simulation, every MMC covers the 10 MW active power demand of its node. This means that there is no load flow between the nodes. At $t = 0\,\mathrm{s}$,

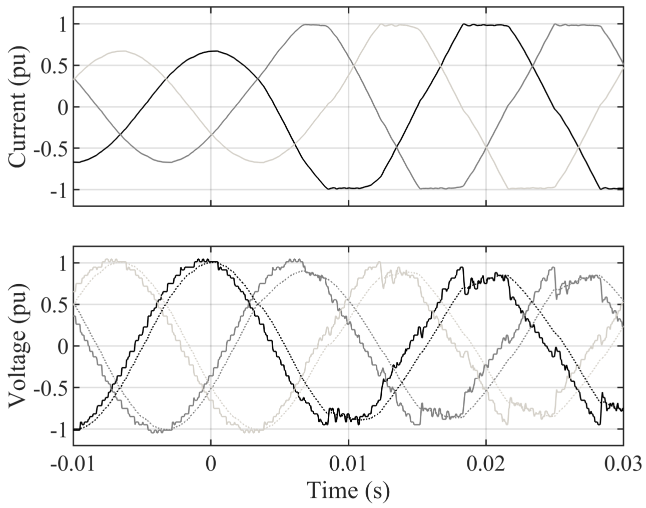

Fig. 4. Inverter current and voltage (—) and grid voltage (···) before and during current limitation.

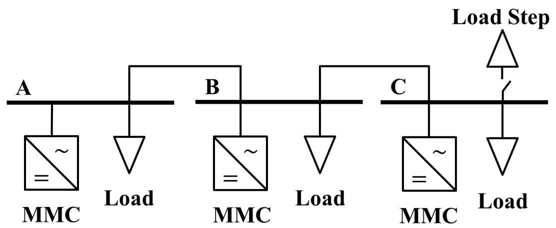

Fig. 5. Grid model of the simulative investigations.

an additional impedance load equivalent to 12 MW is connected to node C, which theoretically should be divided among all feed-ins on the basis of the available MMC active power reserves. All simulations were carried out with the simulation software *PowerFactory*.

In the following, three different scenarios and their simulation results are presented and discussed. In scenario 1, there is no MMC current limitation and every load of each node is a 100 % impedance load. This scenario is for comparative purposes for the following scenarios. In contrast to scenario 1, current limitation of each MMC is set to $i_{\max} = 1\,\mathrm{pu}$ in scenario 2. This provides an insight into the behavior of current limited grid-forming VSC. Finally, in scenario 3, 50 % of the loads of each node are replaced with constant power loads, representing consumers coupled to the grid by means of power electronics. In contrast to impedance loads, the power of constant power loads does neither depend on grid frequency nor on voltage.

The simulation results are shown in Fig. 6. In scenario 1 with deactivated current limitation, the frequency and

Table 1. Grid-Forming Converter Control Parameters

K_θ	2π
K_U	0.05
K_P	10
K_Q	25
i_{th1}	0.005 pu
i_{th2}	0.01 pu
L	25 mH
R	1 mΩ

voltage behavior is dominated by the grid forming VSM control concept, which is comparable to a grid with synchronous generation only. The simulation results of scenario 2 show differences to scenario 1. In particular, the changes in the frequency curves and a stronger temporary decrease in the voltage of node C are noticable. Since the load step takes place at node C, the MMC of this node must first take over most of the load due to its electrical proximity. Compared to scenario 1, the current limitation of the MMC at node C leads to a reduced contribution of active power, which ultimatly leads to changes in the VSC output frequency based on the VSM control concept. In addition, current limitation temporarily reduces the voltage at node C making it impossible to deliver the VSC rated active power at maximum current. Scenario 2 has already revealed a fundamental issue: while the current is limited, active power fed into the grid is reduced due to a possibly lower grid voltage. This reduces the active power input of the VSM control concept ultimatly leading to an acceleration of the virtual flywheel. In case the other MMC can take the resulting load flows, a new stationary state can be achieved. On the other hand, the decreased grid voltage was also helpful in scenario 2 because of a lower active power demand of the connected impedance loads. In Scenario 3, this effect can no longer be fully utilized. Since 50 % of the loads are constant power loads, the voltage drop caused by the current limitation does not lead to the same reduced active power consumption of the loads. However, the VSM control concept of the MMC at note C tries at first to feed out more active power than is possible with a reduced grid voltage. This leads to a large difference at the active power input of the grid-forming inverter control concept with a positive sign. Therefore, the speed of the virtual flywheel of the applied VSM control concept is no longer reduced but increased. Consequently, the control loop is opened. An even stronger acceleration of the virtual flywheel occurs because, analogous to a SG, the synchronizing electrical torque is continuously reduced. One MMC after the other then loses synchronism to the grid and the simulation is stopped after only 0.3 s.

4. CONCLUSIONS AND OUTLOOK

This paper shows possible effects of current-limited grid-forming VSC on power system stability. Using a simplified implementation of a current limitation approach, possible interactions between VSC during times of current limitation can be observed. In the event of an activated current limitation, the voltage at the VSC PCC may drop, which can reduce its active power output so that the VSC grid-forming control loop is no longer closed. This can lead to instability of the VSC and of the entire power system. An increasing proportion of constant power loads exacerbates this issue. Their active power demand is almost independent of grid voltage, so that a voltage reduction due to current limitation of VSC does not lead to a reduced power consumption. The stability issues shown still occur even in the case of sufficient power reserve. This indicates a fundamental problem with grid-forming inverters with current limitation.

The studies in this paper were carried out under simplified assumptions. However, similar situations with regions with

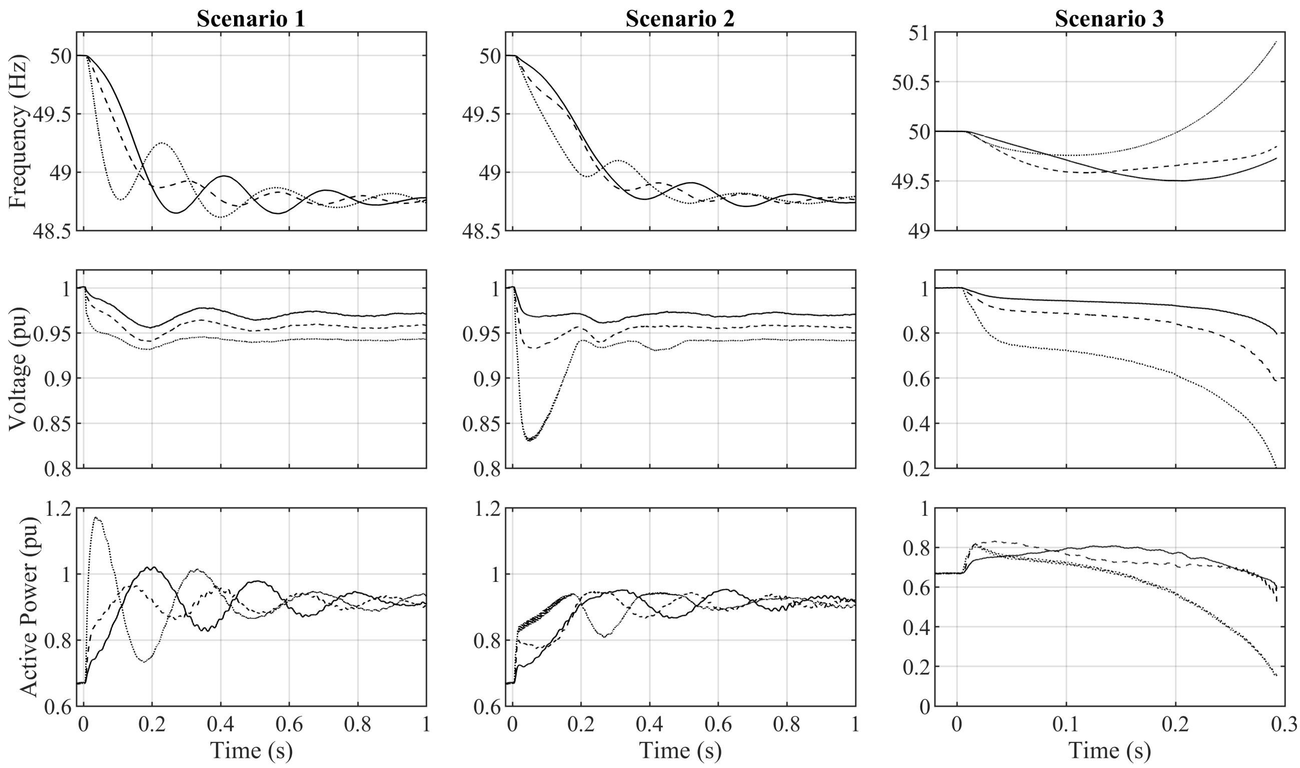

Fig. 6. Simulation results of scenario 1 (100 % impedance loads and no current limitation), scenario 2 (100 % impedance loads with current limitation $i_{\max} = 1$ pu) and scenario 3 (50 % impedance loads, 50 % constant power loads with current limitation $i_{\max} = 1$ pu) at node A (—), B (- - -) and C ($\cdots$)

high shares of grid-forming VSC close to their current limit and high shares of constant power loads may occur in reality. In such situations, a sudden active power shortage must not lead to the shown stability issues. In order to avoid these stability issus, there are basically two possible approaches. On the one hand, the converters could not be operated too close to the current or power limit. However, this leads to a reduced power output and is not optimal for cost reasons. On the other hand, grid-forming control concepts could be revised and an integrated control concept could be developed taking times of current limitation into account. The influence of these newly developed grid-forming control concepts must then be analyzed again in detailed power system studies.

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