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Instability phenomena in interconnected power systems caused by current limitation of grid-forming converters

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***Abstract*—Inertia and voltage source behavior are essential for power system stability. At present, these essential features are provided by synchronous generators (SG). Grid-forming voltage source converters (VSC) can emulate these essential properties of SG and make interconnected power systems with up to 100% converter based generation possible. However, VSC lack an important property of SG: overcurrent capability. Up to now, current limiting has not been considered holistically in most grid-forming control concepts of VSC, although it has a massive impact on their dynamic behavior when active. In this paper, it is shown that this becomes particularly evident in the analysis of transient stability. By means of simulations, the stability behavior of current-limited VSC is compared to the unlimited case. By a synthetic study case and subsequent EMT simulations of a simple transmission system model, we show that there are significant differences and that the transient stability reserve is reduced due to current limitation. If current limiting is not considered in the grid-forming control concept, faults that are easy to cope with in a SG dominated system may lead to instability in power systems with a large share of such grid-forming VSC.**

I. Introduction

Grid-following voltage source converters (VSC) of renewable energy sources (RES) and high-voltage direct current (HVDC) do not contribute to small-signal stability of power systems. The operation of grid-following VSC requires the point of common coupling (PCC) to be characterised by a sufficiently stiff grid voltage. Based on a fast underlying current control strategy, grid-following VSC behave like current sources. This control strategy fulfills an important goal: an exact power feed-in at a given grid voltage and phase angle. This is always accomplished under consideration of the technical current limit, so that overcurrents, which would damage the power electronics of the VSC, are prevented. Additional superimposed control strategies for the provision of ancillary services cannot replace the missing contribution to small-signal stability [1]. Therefore, power system stability is at risk above a certain share of grid-following VSC. Negative consequences in case of high shares of converter based generation are to be expected like higher rates of change of frequency (RoCoF) and local grid voltage instabilities [2]. In fact, in order to maintain power system stability, already today the share of grid-following VSC is limited in some power systems, e.g., in the Irish system [3]. As a consequence, the system contains a minimum share of devices that contribute to small-signal stability. Currently, this is largely achieved using synchronous generators (SG). Their voltage source behavior, together with the provision of system inertia, are essential and a valuable contribution to power system stability.

These voltage source properties of SG have to be replaced by according properties of VSC behavior in order to ensure stable power system operation with very few or even without SG. Grid-forming VSC are considered as a possible solution for interconnected power systems with up to 100 % converter feed-in via HVDC and RES. Such VSC emulate the essential voltage source behavior of SG by means of fundamental adaptations in their control concept. Since the stability of existing power systems is mainly due to SG, the most obvious solution is to mimic their system dynamics. In contrast to SG, the relevant dynamic properties of VSC depend only on the implemented control concept. The additional degrees of freedom have been explored by a wide range of different grid-forming control concepts [4], [5]. They can take advantage of the fast control behavior of VSC without having to emulate the slow and partly negative properties of SG. The developed grid-forming control concepts differ in their dynamic properties and in the way they are synchronised with the grid.

Even though VSC have many advantages compared to SG, a major drawback is given by their very limited capability of providing currents beyond the nominal value. Ignoring this limitation can be considered as equivalent to the requirement that the VSC is over-dimensioned such that the current never reaches this limit. As this is very expensive, there is increased interest in the behavior of GFC when the current limit is reached. While current limiting is easy to implement for current-controlled VSC, this is not the case for grid-forming VSC.

As a matter of fact, the current must not be controlled to a certain set-point but be allowed to react freely after changes in grid voltage phase or amplitude. Only then, the VSC can be truely grid-forming and contribute to small signal stability by behaving as a voltage source with inertia.

If the current limit is reached, however, the current cannot be allowed to react freely. Hence, the control concept deviates from normal grid-forming behavior in order to keep the current within the technical limits of the VSC. Consequently, under active current limiting, the grid-forming VSC will deviate from its normal grid-forming behavior, irrespective of the concept actually implemented. It is obvious that this has an effect on the dynamic behavior of the power system. In order to evaluate such effects, simulation models of interconnected power systems must take the behavior of current-limited grid-forming VSCs into account. Otherwise, fundamental effects are neglected, which could lead to invalid results of stability studies. While there are elegant solutions to prove power system stability based on sytem theory as in [6], these solutions are not valid when non-linear effects such as current limitation occur. Currently, the number of studies that take current limitation of grid-forming VSC into account is increasing. Undesirable effects of current limitation of grid-forming VSC are shown in [7] with regard to both voltage behavior and active power behavior using simulations. In [8], the statements on the stability limit of current-limited VSCs were developed with a simplified quasi-stationary model.

The question of which influence the current limitation of grid-forming VSC has on the stability behavior of transmission grids is still open. To our knowledge, this influence has not yet been investigated for transmission grids, even though, there are similar studies on the stability of micro-grids [9]. Therefore, we investigate possible effects using a simplified model of a Modular Multilevel Converter (MMC) [10], a common kind of VSC, and a simplified nine-bus transmission system. First, we introduce the model for an MMC with grid-forming control including current limiting. By means of synthetic scenarios, the behavior of this model in case of short circuits and phase angle jumps is then analysed and compared with the behavior without current limitation. Finally, the influence of current limitation of grid-forming MMC on the transient stability behavior of a nine-bus transmission system is investigated.

II. Model of a Grid-Forming Modular Multilevel Converter

The main task of the control concept of the MMC is to achieve grid-forming behavior. This implies voltage source behavior without fast current control. Depending on the grid situation or in case of faults, high currents can occur which could damage the MMC. To protect the MMC hardware, the resulting currents must therefore be kept within the technical current limits by the MMC control concept.

An overview of the control concept and the MMC model used is shown in Fig. 1. The MMC is connected to the grid via a reactance X_{MMC}. Since the perspective from the grid on the behavior of the converter is of particular interest for the investigations in this paper, internal converter processes can be neglected. As a first simplification, the DC voltage is considered as constant, thus neglecting related dynamics of HVDC or RES that occur in reality. The second major simplification is the use of an Average Value Model (AVM) to represent the MMC. This simplification neglects, among other things, more complicated superimposed submodule (SM) control algorithms. Based on the number of active SM, $\hat{N}_{\mathrm{abc}}$, the AVM provides a corresponding three-phase voltage. The input of the overall control concept are the voltages $\tilde{u}_{\mathrm{abc}}$ at the point of common coupling (PCC) and the MMC currents $\tilde{i}_{\mathrm{abc}}$. In order to achieve grid-forming behavior under consideration of the current limits, four essential blocks are required in the control setup. Each block of this control setup is described in the following subsections.

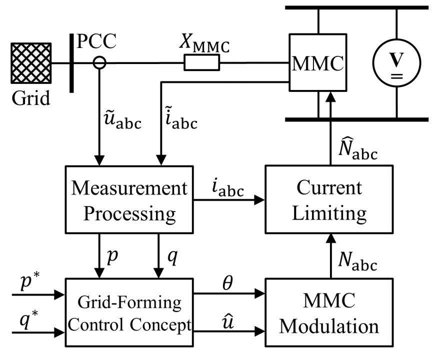


Fig. 1. Overview of the grid-forming MMC model.

A. Measurement-Processing

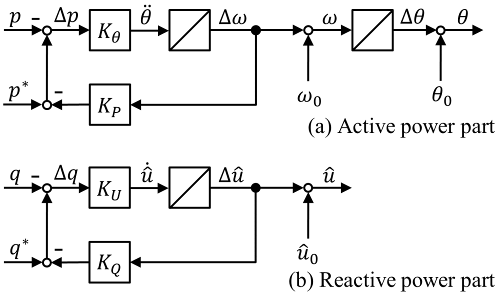
To control the MMC voltages and currents, selected quantities must be measured. In reality, these quantities are not instantly available. In order to model this measurement process, the variables are delayed in the measurement-processing block and are prepared for the subsequent grid-forming control algorithm and current limiting approach. The measurement delays of the three-phase grid voltage $\tilde{u}_{\mathrm{abc}}$ at the PCC and the measurement of the MMC currents $\tilde{i}_{\mathrm{abc}}$ are modeled by means of first order lags. Subsequently, 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 $100\,\mu\mathrm{s}$ and for power measurements to $4\,\mathrm{ms}$.

B. Grid-Forming Control Concept

The majority of grid-forming control concepts are based on power synchronisation. Differences are mainly found in the dynamics between the power inputs p and q and the outputs relevant for the VSC behavior at the PCC, the 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.

A widespread and obvious option for power synchronisation is to mimic the, possibly simplified, dynamics of a SG, which is well-known as the virtual synchronous machine (VSM) [11]. Fig. 2(a) shows a possible active power part of a VSM based on the well-known swing equation. Analogous to SG, a difference in active power is interpreted as the angular acceleration $\ddot{\theta}$ of a virtual flywheel, characterized by K_θ analogous to the acceleration time constant of SG. Additional damping is achieved by means of a frequency droop characterized by K_P based on the frequency deviation $\Delta\omega$. Such a damping term differs from the behavior of a real SG in the sense that it corresponds to instantaneous provision of frequency containment reserve (FCR). Real SG that provide FCR need a change of the mechanical power to do so, which cannot take place instantaneously due to the dynamics of the process that drives the turbine. This is an important difference between VSM and SG. The VSC frequency ω is calculated by one-time integration of $\ddot{\theta}$. Further integration results in the output θ.

Analogously, Fig. 2(b) shows the corresponding reactive power part of a VSM. A difference in reactive power



(a) Active power part

(b) Reactive power part

Fig. 2. Grid-forming Swing-Equation Control Concept, consisting of the active power part (a) and the reactive power part (b).

is interpreted as the rate of change of the VSM voltage amplitude $\hat{u}$ characterized by K_U analogous to the excitation time constant of SG. Damping is achieved by means of a voltage droop characterized by K_Q based on the internal voltage deviation.

It should be noted that the presented VSM is equivalent to the grid-forming control concept *Droop* with regard to dynamics [12]. Parameters can be converted, so that the results of our contribution are directly applicable to both the VSM and the Droop grid-forming control concepts.

C. Modular Multilevel Converter Modulation

In order to forward the output variables (voltage amplitude $\hat{u}$ and phase angle θ) of the grid-forming control concept to the AVM, they must then be transformed into a number N_{abc} of SM that are to be activated. First, a three-phase voltage signal $e_{\text{abc}} = \hat{u}\sin(\theta + \theta_{\text{abc}})$ 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) [13], resulting in the number of active SM $N_{\text{abc}} = \{N_{\text{a}}, N_{\text{b}}, N_{\text{c}}\}$ for each phase.

D. Current Limiting

A simplified modelling of current limiting is sufficient to investigate the repercussions of current-limited MMC on power system stability. In this paper, the heuristic control approach for current limiting of MMC [7] is used. The basis of this heuristic current limiting approach is the adaptation of the voltage amplitude difference between the PCC and generated MMC voltage via the filter X_{MMC} when approaching the current limit. The converter currents are then clipped above a certain limit, maximising current output during active current limiting. This requires highly accurate measurements of the MMC currents and voltages at the PCC within a few µs. By means of successive activation and deactivation of SM of each individual phase, the voltage amplitude difference via X_{MMC} can be adjusted in such a way that the currents do not reach unacceptably high values. The currents are not controlled directly by this approach, so the grid-forming voltage source behavior is maintained.

Fig. 3 illustrates the dynamic behavior of the current limiting approach used in this paper. For the purpose of illustration, the converter currents initially are allowed to exceed the actual current limit of $i_{\max} = 1.05$ pu, meaning that current limiting is inactive. At $t = 0\,\text{s}$, current limiting is activated, which leads to an immediate adjustment of the MMC voltages and ultimately to a nearly trapezoidal shape of the currents in order to keep the current below $i_{\max}$.

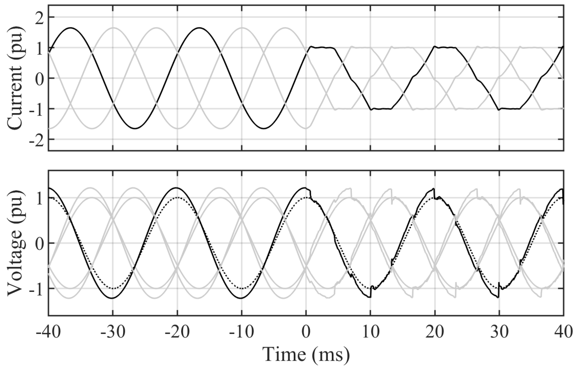


Fig. 3. Converter current and voltage (—) and grid voltage (· · ·) before and during current limiting.

III. Synthetic Studies using a Voltage Source with variable Phase and Voltage

Synthetic studies with an ideal voltage source allow insights into the effect of current limiting without superimposed influences of other dynamics of loads or generators. For this reason, the stability behavior of a grid-forming MMC is examined in a synthetic network model first. The network model is shown in Fig. 4 and consists of an MMC with a filter reactance X_{MMC}, a node, and a voltage source with coupling reactance X_{VS} as an equivalent of transformers and lines. Frequency and amplitude of the voltage source are constant.

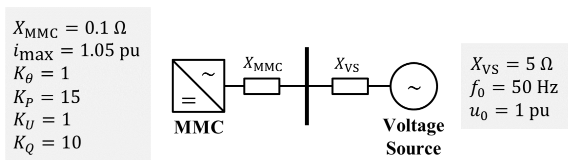


Fig. 4. Network model of the synthetic investigations.

In the following, two different types of disturbances are considered: a complete three-phase short circuit near the generator and a phase angle jump. At the beginning of the simulations, the MMC is operated at $p = 0.5$ pu. The simulations are carried out with current limiting active and inactive in order to show the influence of current limitation on transient stability. All simulations were carried out with the simulation software *PowerFactory* in the EMT domain.

The simulation results in the first column of Fig. 5 were carried out without current limitation for two closely spaced short circuit clearing times $t_{\text{SCCT}} = 240\,\text{ms}$ and $250\,\text{ms}$. In the beginning, the results of the two simulations are identical. Immediatly after the short circuit, there is a large jump in the converter current. During the fault, the phase angle difference between the MMC and the voltage source increases. This is due to the fact that the MMC only feeds in reactive power during the fault, which, as with the SG, leads to a strong acceleration of the virtual flywheel. In case of the smaller t_{SCCT}, the virtual flywheel of the MMC can synchronise

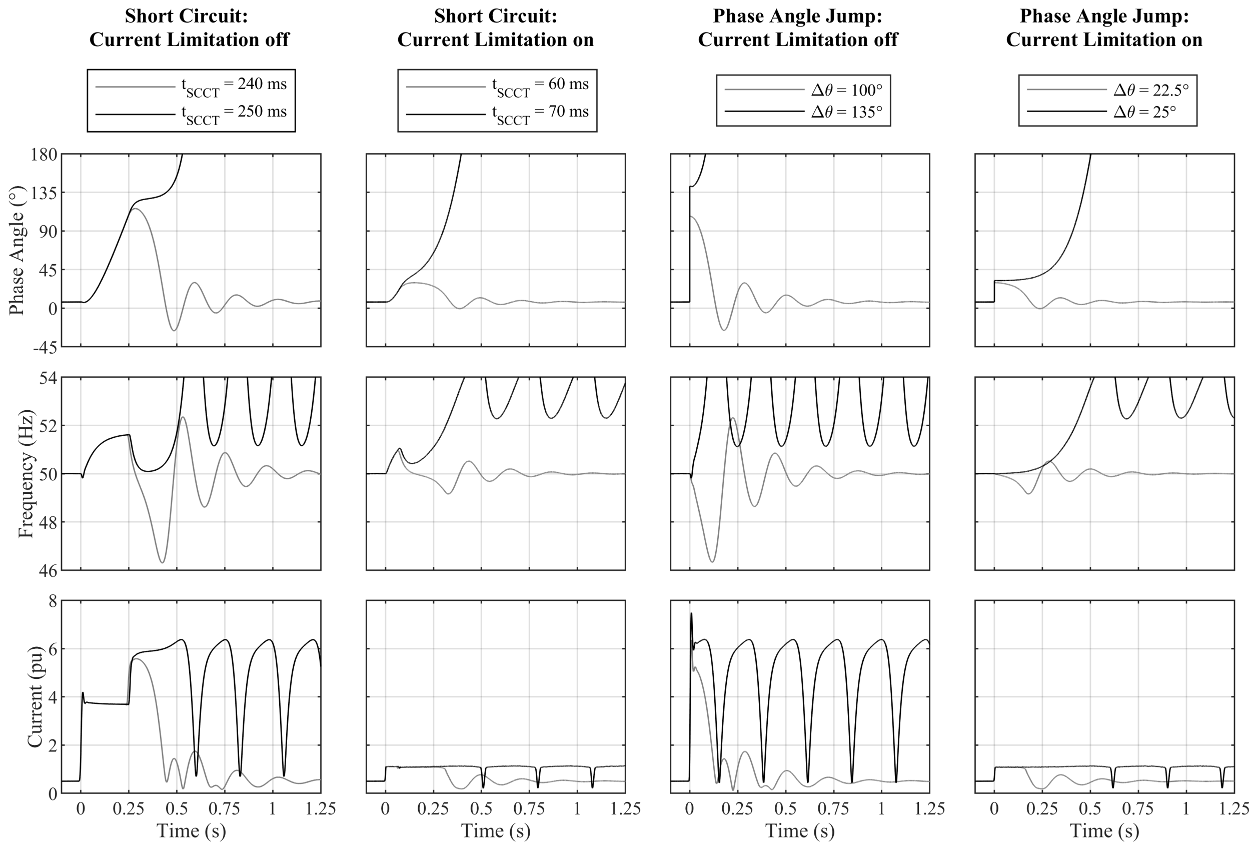


Fig. 5. Simulation results of the synthetic studies for two short circuit clearing times t_{SCCT} at the PCC and two different phase angle jumps, each with and without current limitation.

again with the voltage source after clearing. Apart from the flattened frequency response, which results from the frequency droop, the behavior is very similar to SG, so that classic stability criteria can be applied to a certain extent. The greater t_{SCCT}, however, leads to an unstable behavior in which the virtual flywheel is not able to stay synchronized with the voltage source.

With active current limiting, the behavior is completely different, as shown in the second column of Fig. 5. The clearing times considered are now $t_{\mathrm{SCCT}} = 60\,\mathrm{ms}$ and $70\,\mathrm{ms}$. Despite active current limiting, the curves at the beginning of the simulations are very similar compared to the unlimited cases. However, while the case with $t_{\mathrm{SCCT}} = 60\,\mathrm{ms}$ is stable, a non-intuitive and non-linear behavior of the frequency can be observed after the fault. It becomes clear that the maximum phase angle and clearing time at which the MMC and the voltage source loose synchronism is significantly lower when current limiting is active. Classical stability criteria, such as the equal area criterion, are not applicable anymore in the case of active current limiting due to the resulting non-linear characteristics. It can be concluded that the maximum short circuit clearing time may be significantly reduced in the case of grid-forming VSC due to current limits.

The simulation results for phase angle jumps without current limitation are shown in the third column of Fig. 5. The phase angle jumps are performed abruptly at $t = 0\,\mathrm{s}$ by the voltage source, so that the phase angle differences between the MMC and the voltage source change abruptly in the simulations. This leads to an immediate change in power feed-in. The grid-forming concept tries to reach the original phase angle difference. This state can only be achieved by a temporary frequency adjustment. With a phase angle jump of $100°$, the original phase angle difference can be reached again after a well damped oscillation. In case of a phase angle jump of $135°$, however, there is no synchronising process immediately after the phase angle jump, so that the MMC immediately loses synchronism with the voltage source.

The simulated phase angle jumps of up to $135°$ may probably never occur in reality. However, the simulations show that there is a considerable stability reserve with respect to phase angle jumps, which illustrates why phase angle jumps are no relevant disturbance with respect to stability analysis of SG. In contrast, the stability margin for VSM with current limitation is significantly lower, as can be seen in the fourth column of Fig. 5. After a phase angle jump of $22.5°$, synchronisation with the voltage source can still be achieved. When the phase angle jump is $25°$, this is no longer possible and the MMC loses synchronism with the $50\,\mathrm{Hz}$ system.

IV. Transmission System Studies

This section focuses on the possible effects of current limitation of grid-forming VSC on power system stability of interconnected power systems. The nine-bus transmission system model shown in Fig. 7 is used for this purpose. The model is a simplified version of the transmission system of

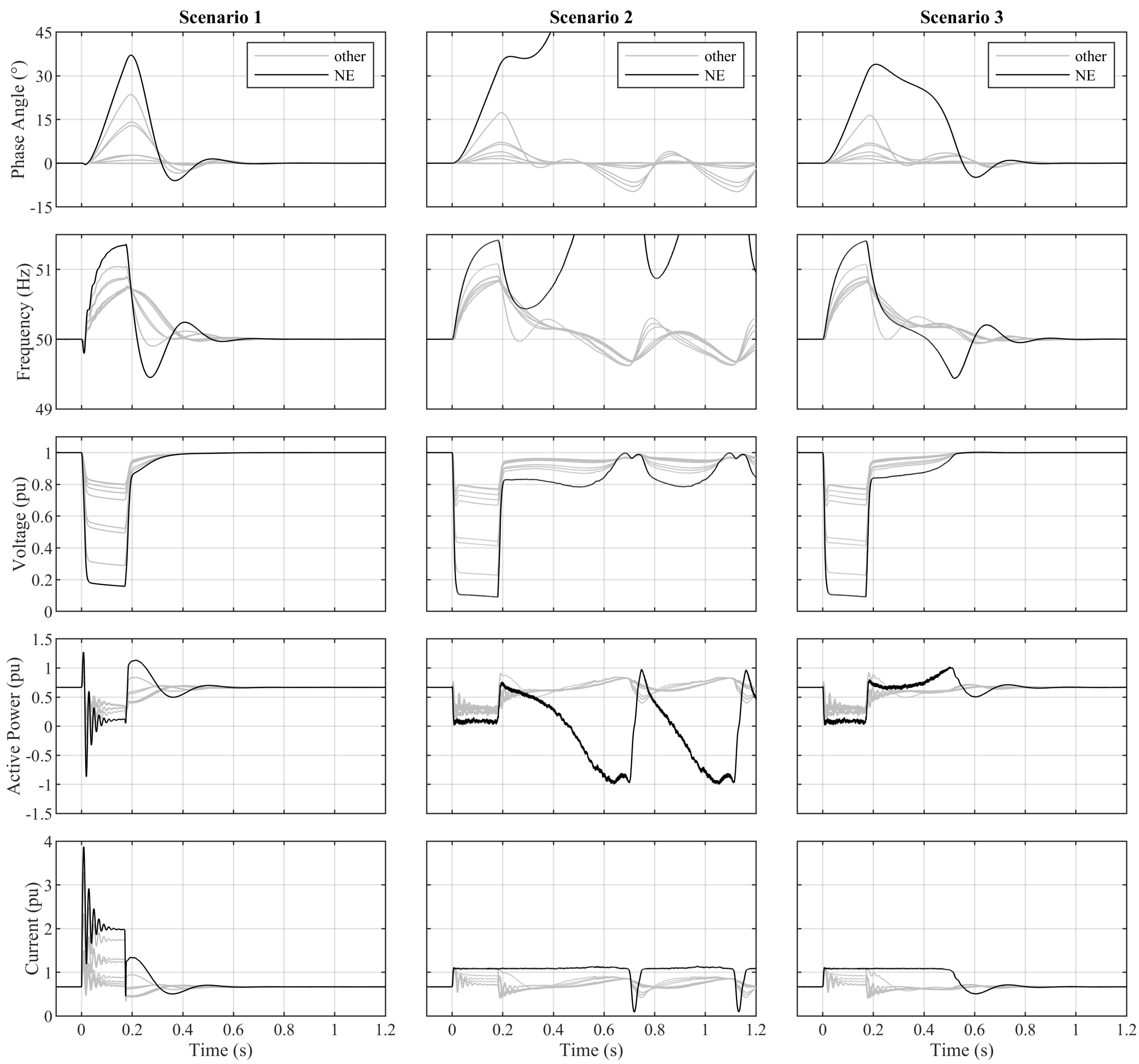


Fig. 6. EMT-Simulation results of the interconnected power system studies in case of a three-phase short circuit between the nodes NW and N of scenario 1 (short circuit clearing time $t_{\mathrm{SCCT}} = 180\,\mathrm{ms}$ and no current limitation), scenario 2 ($t_{\mathrm{SCCT}} = 180\,\mathrm{ms}$ with current limitation $i_{\max} = 1.05$ pu) and scenario 3 ($t_{\mathrm{SCCT}} = 170\,\mathrm{ms}$ with current limitation $i_{\max} = 1.05$ pu). The angle differences are shown with respect to the angle of node S.

the German federal state of Baden-Württemberg. Comparable line lengths and parameters are used. The network is operated as an island so that only effects within the network are considered. One MMC with current limiting with the nominal apparent power $S_{\mathrm{rated}} = 1.5\,\mathrm{GVA}$ and an impedance load with $P_0 = 1\,\mathrm{GW}$ is connected to each node. Each MMC of each node supplies this impedance load, so that there is no power exchange between the nodes. The same MMC parameters apply as in Fig. 4.

At $t = 0\,\mathrm{s}$, a complete three-phase short circuit is simulated on the line between the nodes N and NE. The simulations are intended to show differences in the stability behavior due to the current limitation of MMC. For this reason, simulations are performed with activated and deactivated current limitation and different short circuit clearing times t_{SCCT}.

The simulation results are shown in Fig. 6. In the first scenario, the short circuit lasts for $t_{\mathrm{SCCT}} = 180\,\mathrm{ms}$. With

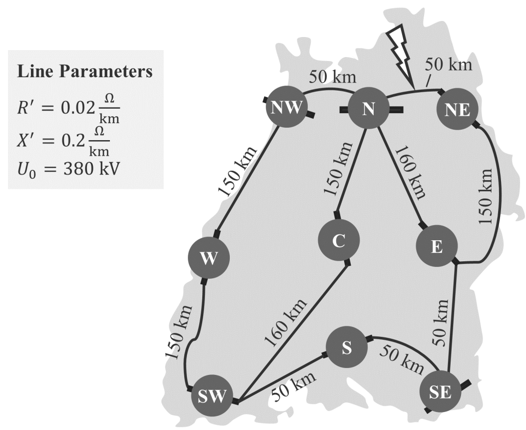


Fig. 7. Transmission system model based on a simplified version of the transmission system of the German federal state of Baden-Württemberg.

current limiting deactivated, the behavior is similar to a network with SG-based generation only. As a result of the short circuit and the associated undervoltage, the original active power cannot be delivered by the MMCs, which leads to an increase in frequencies and phase angle differences. The effects of the short circuit on the MMCs are stronger the closer they are to the short circuit. The node NE is most affected because of its loose coupling with the grid after the fault. The simulation results of node NE are therefore highlighted and show the most pronounced behavior. After fault clearing, a short transient process takes place and the initial system state is reached again.

In scenario 2, current limiting is activated, which leads to an unstable sytem behavior of the MMC at node NE for the same $t_{\mathrm{SCCT}} = 180\,\mathrm{ms}$ as in scenario 1. Except for the active power and current curves, the simulation results are initially very similar to scenario 1 during the short circuit. However, the MMC at node NE loses synchronism to the remaining network after fault clearing. Frequency and phase angle difference change into a nonlinear oscillation asynchronous to the remaining network.

A reduction of the fault clearing time to $t_{\mathrm{SCCT}} = 170\,\mathrm{ms}$ in scenario 3, however, leads to a stable system behavior with activated current limiting. It becomes clear that the MMC at node NE remains in current limitation for a certain period of time even after fault clearing. During this period of maximum current output, an undervoltage is visible, which limits the maximum active power output. Afterwards, the MMC operates again according to its grid-forming control. The non-linear influence of current limiting is again clearly visible in the frequency and phase angle behavior after the fault.

V. Conclusion and Outlook

This paper provides further insights into the stability behavior of grid-forming VSC with current limiting. On the basis of [7], it takes a closer look at the stability limits of grid-forming VSC. For this purpose, investigations are carried out using a simplified model of an MMC in verious scenarios using a synthetic network and a simplified transmission grid. In order to show the influence of current limitation on power system stability, short circuits and phase angle jumps are investigated. The results show that the dynamic power system behavior will change due to current limiting of grid-forming VSC and the limits of stable power system operation will be tightened in case of disturbances. In the worst case, individual grid-forming VSC can lose synchronism with the remaining grid. Since overdimensioning of the VSC does not represent a cost-optimal solution for this problem, the grid-forming control concepts must be revised with regard to the interaction between the grid-forming control concept and current limiting.

The purpose of this paper is to illustrate the effects of a non-considered limitation within a control system. New control concepts have to consider current limiting and must work reliably with all defined types of faults. The influence of new developed grid-forming control concepts must then be analyzed in detailed power system studies.

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References

[1] D. Duckwitz and B. Fischer, “Modeling and Design of df/dt-Based Inertia Control for Power Converters,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 4, pp. 1553–1564, 2017.

[2] ENTSO-E, “High Penetration of Power Electronic Interfaced Power Sources (HPoPEIPS),” 2017.

[3] PPA Energy, “Rate of Change of Frequency (ROCOF) - Review of TSO and Generator Submissions - Final Report,” Guildford, Surrey, UK, 2013.

[4] D. Duckwitz, “Power System Inertia,” Ph.D. dissertation, Fraunhofer IEE, Kassel, 2019.

[5] B. Weise and A. Korai, “Control concepts for power electronic interfaced generating units for improvement of power system stability: Direct voltage control as a solution approach,” in *13. ETG/GMA-Fachtagung Netzregelung und Systemführung*.

[6] G. Weiss, F. Dörfler, and Y. Levron, “A stability theorem for networks containing synchronous generators,” *Systems & Control Letters*, vol. 134, p. 104561, 2019. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0167691119301719

[7] C. Schöll and H. Lens, “Impact of Current Limitation of Grid-forming Voltage Source Converters on Power System Stability,” *Conference Proceedings: 21st IFAC World Congress*, 2020.

[8] T. Qoria, F. Gruson, F. Colas, G. Denis, T. Prevost, and X. Guillaud, “Critical Clearing Time Determination and Enhancement of Grid-Forming Converters Embedding Virtual Impedance as Current Limitation Algorithm,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 2, pp. 1050–1061, 2020.

[9] A. D. Paquette and D. M. Divan, “Virtual Impedance Current Limiting for Inverters in Microgrids With Synchronous Generators,” *IEEE Transactions on Industry Applications*, vol. 51, no. 2, pp. 1630–1638, 2015.

[10] A. Lesnicar and R. Marquardt, “An innovative modular multilevel converter topology suitable for a wide power range,” in *2003 IEEE Bologna Power Tech Conference Proceedings*. IEEE, June 23-26, 2003, pp. 272–277.

[11] H. Wrede and P. Winter, “Verhalten von Umrichtern am Netz: Beiträge der 12. ETG/GMA-Tagung Netzregelung und Systemführung,” in *12. ETG/GMA-Fachtagung Netzregelung und Systemführung*, 2017, vol. 153, CD-ROM.

[12] S. D’Arco and J. A. Suul, “Equivalence of Virtual Synchronous Machines and Frequency-Droops for Converter-Based MicroGrids,” *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 394–395, 2014.

[13] Y. Wang, C. Hu, R. Ding, L. Xu, C. Fu, and E. Yang, “A Nearest Level PWM Method for the MMC in DC Distribution Grids,” *IEEE Transactions on Power Electronics*, vol. 33, no. 11, pp. 9209–9218, 2018.