This paper was presented at the 22st Wind & Solar Integration Workshop (2023) and published in the workshop's proceedings

The Influence of Grid-Forming Loads on Transient Stability

Nils Wiese[1]* , Baran Karadag[2], Martin Braun[1,3]

[1] *Department of Energy Management and Power System Operation, University of Kassel, Wilhelmshöher Allee 73, Kassel, Germany*
[2] *Statkraft Germany GmbH, Düsseldorf, Germany*
[3] *Fraunhofer IEE, Joseph-Beuys-Straße 8, Kassel, Germany*
**E-mail: nils.wiese@uni-kassel.de*

Keywords: GRID-FORMING LOAD, CURRENT LIMITATION, TRANSIENT STABILITY

Abstract

With the integration of renewable energies the share of inverters in the grid increases and thus the inertia of the system is weakened. Grid-forming inverter coupled loads can contribute to system inertia. Handling of short circuits becomes a challenge. In contrast to synchronous generators, a grid-forming inverter coupled load decelerates during a fault, in dependence on the grid-forming control, and can shorten the critical clearing time of the system. In this paper, we present a control scheme based on the virtual synchronous machine for a grid-forming inverter coupled load and propose different methods that change the frequency behavior during fault. Therefore, different current limitation methods and the adjustment of parameters during fault are analyzed. Good transient stability can be achieved with the help of the appropriate method and parameterization. Changing the inertia constant and adjusting the active power setpoint have proven to be particularly effective which is shown in MATLAB/Simulink simulations.

1 Introduction

The global power system is undergoing an extensive transition. The share of renewable energies and batteries increases constantly, posing new challenges for power system stability. With the integration of renewable energies the share of inverters in the grid increases and thus the inertia of the system is weakened. A stable power system cannot be achieved with traditional current-controlled inverters [1]. Therefore, grid-forming controls were developed. Grid-forming inverters can replace synchronous generators and make fully inverter-driven grids possible [2]. Grid-forming controls offer a high degree of freedom in their design process and offer new possibilities regarding the utilization of generators and loads. A high inertia constant of the grid is desired and operators want or have to achieve this cost efficiently. For this reason, concepts like asymmetrical inertia provision were developed. An overview is given in [3]. In this concept, renewables offer inertia in case of a rising frequency and loads contribute to inertia in case of a falling frequency. This is hoped to improve frequency stability. The simplest load you can think of is a charging battery interfaced with the grid with a grid-forming inverter. Such a battery might be crucial to guarantee power system stability. This poses the challenge, that the battery has to stay connected in case of a short circuit even when it charges. Under these circumstances, a grid-forming inverter will decrease its frequency because the control tries to reach the power setpoint. All synchronous generators (or grid-forming inverters injecting power) will accelerate. The angle divergence will rise fast and loss of synchronism can be the result if an angle divergence of 180° is reached. Especially in situations where the coupling is particularly weak between the grid-forming inverter coupled load and the grid, the angle divergence rises fast. Due to this, the critical clearing time of the system is decreased compared to a system without grid-forming inverter coupled loads [4]. In the future, several load types seem to be suitable for grid-forming operation like electric vehicle charging or heating and cooling processes [3]. At this point, it is worth mentioning that a grid cannot be formed with loads, except for energy storage devices. Nevertheless, for simplicity, the term grid-forming load is used in this paper.

The typical low overcurrent capability of power electronics decreases the critical fault clearing time in comparison to a synchronous generator [5]. In the literature, several authors addressed the challenges of grid-forming inverters with regard to short circuits. In particular, current limitation, voltage support and transient stability were tackled. All these points are addressed with the presented controls. Several possible solutions, that improve the inverter's frequency behavior, were already presented [6–9]. It seems plausible, that also a grid-forming control for loads can be designed in a way that improves the frequency behavior. In [4] no satisfying solution was found when a grid-forming load has to deal with a rising grid frequency during fault. Based on the experiences for grid-forming inverters working as generators in [7], the control was further improved by adjusting the parameters of the virtual synchronous machine (VSM) during fault. Due to this the critical clearing time can be improved. In this paper, the control scheme does not use an underlying current control loop for current limitation which affects small-signal stability [10]. A temporary current control or a high virtual impedance is used. Due to the proposed methods, transient stability can be improved and offer the possibility for the integration of grid-forming loads, with less negative impact on the critical clearing time of the power system.

In this paper, we introduce the developed grid-forming control for a load. Furthermore, we will show how the fault behavior of a grid-forming inverter working as a load can be changed in order to achieve better transient stability. Different methods for the manipulation of the frequency behavior during fault will be described and assessed in simulations. At the end, we discuss the results and give an outlook for further work.

2 Control Approach

In the following section, we show the used implementation of the virtual synchronous machine. Furthermore, we show the different methods for current limitation.

2.1 Grid-forming Control

In this paper we use the approach from [11] for the virtual synchronous machine but neglect the reactive power droop. The inverter control scheme is depicted in Figure 1. T_A is the acceleration time constant of the VSM. P^{ref} is the active power reference and P_p is the power from proportional frequency control. The active power P has to be calculated from measured converter voltage v_{abc} and current i_{abc}.

$$\dot{\omega} = \frac{1}{T_A}(P^{ref} - P - P_p) \tag{1}$$

The internal rotor angle δ_i is calculated by equation 2 with the help of the nominal frequency ω_0.

$$\dot{\delta}_i = \omega\omega_0 \tag{2}$$

Forward damping is implemented by equation 3 and the corresponding damping constant k_{df}.

$$\delta = \delta_i + k_{df}\omega_0(\omega - \omega_{ref}) \tag{3}$$

P_p is calculated by equation 4.

$$P_p = k_{pf}(\omega - \omega_{ref}) \tag{4}$$

The amplitude of the virtual rotor voltage e is calculated in equation 5 and T_v describes the used time constant. The voltage phasor is aligned with the d-axis, see eq. 6. Reactive power is controlled by adjusting the amplitude of the voltage phasor. Voltage amplitude and its angle δ are the outputs of the VSM.

$$\dot{e} = \frac{1}{T_v}(e^{ref} - e) \tag{5}$$

$$e = \begin{bmatrix} e & 0 \end{bmatrix}^T \tag{6}$$

A lead-lag filter, eq. 7, with high-pass characteristic, damps the LC-resonance.

$$G_{ad}(s) = k_{ad}\frac{s + \omega_{lead}}{s + \omega_{lag}} \tag{7}$$

A virtual circuit G_{vi} is formed by a virtual reactance x_v and a transient resistor r_v, see eq. 8.. The measured converter current causes a virtual voltage drop v_{vc} and is subtracted from the VSM voltage. For the transient resistor a high-pass characteristic with time constant τ_{rv} is chosen as shown in equation 9. The effect of the transient resistor is, that it limits the increase of the current if a fault occurs and it provides damping.

$$u_{vc} = \begin{bmatrix} r_v & 0 \\ 0 & r_v \end{bmatrix} G_{rv}(s) \cdot i_{dq} + \begin{bmatrix} 0 & x_v \\ -x_v & 0 \end{bmatrix} \cdot i_{dq} \tag{8}$$

$$G_{rv}(s) = \frac{s}{1 + \tau_{rv}s} \tag{9}$$

The virtual circuit can further be used to limit the fault current. This is explained in detail later.

In the control scheme is also a current controller shown, which is used for current limitation in two methods. This is explained in the next subsection.

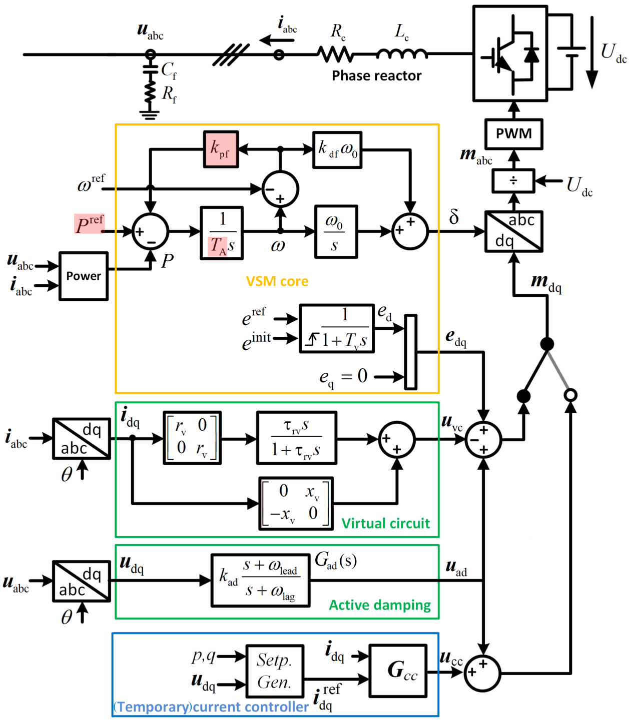

Fig. 1. Control scheme of the grid-forming inverter

With the help of the previous equations the modulation m_{dq} in dq-quantities is calculated. The measured DC voltage U_{DC} is then used to calculate the three-phase modulation index m_{abc}.

2.2 Current Limitation

In this paper we use different methods for current limitation. These three methods are explained below.

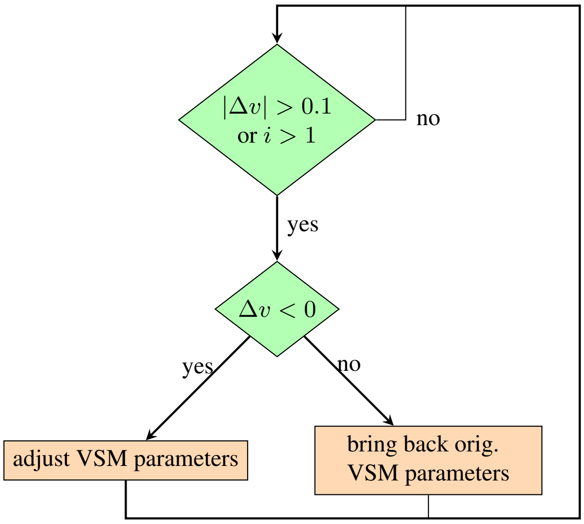

Fig. 2. Flowchart for control with high virtual impedance

2.2.1 High Virtual Impedance: As already discussed in the literature a virtual impedance can be used to protect the inverter from overcurrents [12]. With the value of the virtual impedance the current limitation can be tuned as it influences the voltage drop over the virtual impedance and therefore the current, see also equation 8.

During the fault parameters of the VSM can be adjusted. A fault is detected by current and voltage measurement. After the fault the original parameters are restored. This is shown in flowchart 2. Δv is calculated with the measured voltage and its value $2\,\mathrm{ms}$ ago. If the calculated value is smaller zero, there is a voltage sag. A positive value indicates fault clearing.

2.2.2 Temporary Current Control: Temporary current control means, that in case of a detected fault, the VSM is deactivated and current control is activated, see [6]. After limiting the current successfully the current control (CC) is deactivated and the VSM re-initialized. Therefore, the inverter keeps its grid-forming functionality during fault. When the fault is cleared, current control is activated again and limits the current. Afterwards, it is deactivated and the VSM takes over. In the original concept, the active power setpoint was already adjusted in order to achieve better transient stability. In [7] the active power setpoint adjustment and re-initialization process was further improved. In this paper we use a standard proportional-integral controller (G_{CC}) for the current control. In contrast to a conventional current-controlled inverter, we use the reference frame of the VSM instead of a phase-locked loop. The reference frame of the VSM is frozen when current control is activated. Due to this, the d-axis is not aligned anymore with active power. For this reason the current setpoints i_{dq}^{ref} have to be generated by the measured active and reactive power (q) and the measured voltage. This is done in the setpoint generator. To ensure voltage support the current controller feeds in purely reactive current with an amöitude of $1\,\mathrm{pu}$. The current control is also depicted in Figure 1.

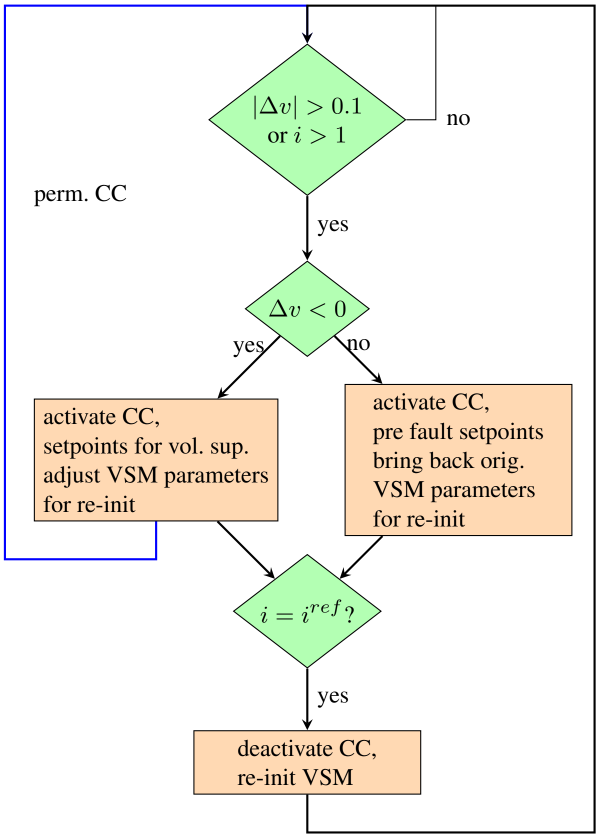

Fig. 3 Flowchart for temporary current control - blue path is used for permanent current control

After reaching the current setpoints, the VSM is re-initialized (deactivation of current controller) in order to keep grid-forming functionality during fault. During the fault the inverter should feed in the same active and reactive power as the temporary current control did. The VSM is re-initialized in the way, that the VSM provides the same voltage phasor as the current control did in a global reference frame. Further explanation can be found in [13]. Another requirement is, that the power setpoint is adjusted. It needs to equal the active power fed in at the end of the current control period. If this is the case, no power imbalance occurs and therefore no change of frequency during the fault if the grid frequency stays constant. Furthermore, all filters have to be re-initialized.

For fault clearing the same procedure is performed. The current setpoints are the pre-fault values of the current. The procedure of temporary current control is shown in flowchart 3. During and after the fault parameter adjustment can be performed.

2.2.3 Permanent Current Control: The method of permanent current control is similar to the previous one. The only difference is, that it does not re-initialize the VSM during the fault. This difference is shown by the blue path in Figure 3.

2.2.4 Parameter Adjustment: A well-known conventional approach to assess the transient stability of a synchronous generator is the use of the so-called equal area criterion [14]. There

it is shown, that the critical clearing time is mainly influenced by the input power, the impedance of the system, and the inertia of the generator.
In contrast to a synchronous generator, the behavior of the VSM during a short circuit can be designed by changing its parameters. In this paper the parameters k_{pf}, T_A and k_{pf} were chosen to shape the behavior. The parameters are highlighted in red in Figure 1.

A reduction of T_A allows the VSM to follow changes of the grid frequency faster in case of a rising frequency during a fault. On the other hand, a higher T_A suppresses fast changes of the VSM frequency. An adjustment of the active power setpoint can decrease the power imbalance of the VSM and thus slow down changes of the VSM frequency. In [4] it was shown that an increase in k_{pf} slows down a grid-forming inverter working as a generator. In case of a rising grid frequency a lower k_{pf} allows the VSM to follow the grid frequency better.

3 Simulation

The simulation of the proposed inverter is performed in MATLAB/Simulink. The inverter is connected to a stiff external (ex.) grid via a simple r/l representation of a feeder line (Z_{line}). The grid has an impedance, namedas Z_{grid}. The test system is shown in Figure 4. The fault is imposed by connecting a low impedance resistor R_f from the three phases to ground. The fault is cleared by the disconnection of R_f. The values of the grid and current control are listed in table 1. The parameters of the VSM control and LC-filter are adopted from [11].

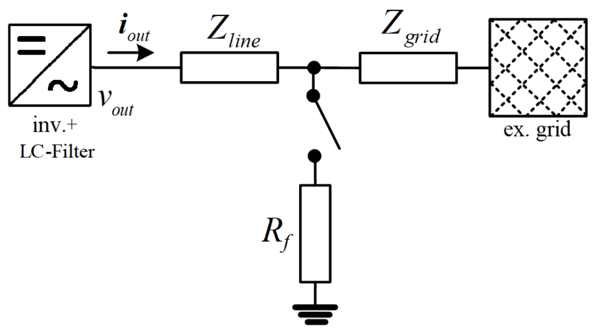

Fig. 4. Simulation test system

Table 1 Simulation parameters

Description	Symbol	Value
line impedance	Z_{line}	$0.01 + 0.1i$ pu
grid impedance	Z_{grid}	$10e^{-6} + 500ie^{-6}$ pu
fault impedance	R_f	$220ie^{-6}$ pu
base voltage	–	326.6 V
base current	–	183.7 A
integral gain	k_{icc}	280
proportional gain	k_{pcc}	0.35

In the simulation model of the inverter controllable voltage sources are used instead of switching semiconductors. Despite that, a current limit of $1\,\mathrm{pu}$ is set if current control is used. Furthermore, voltage support is given by prioritizing reactive current injection during the fault. In this paper, we assume the use of an inverter, which is able to handle positive and negative active and reactive power flows. Possible restrictions by the load are out of scope and discussed later.

In cases, where the virtual impedance is used for current limitation, the virtual impedance was increased for this purpose. In all scenarios, a fault duration of $200\,\mathrm{ms}$ was chosen. Except the first one, which is used to illustrate the already explained problem. The active power setpoint is $-50\,\%$ of nominal power. The voltage is controlled to $1\,\mathrm{pu}$.

3.1 Scenarios

All previously shown control methods for current limitation are analyzed in the simulation scenarios.

In order to analyze the effects of a rising grid frequency, the external grid frequency is increased during the fault as shown in Figure 5. The effects of a constant grid frequency are also analyzed.

When parameter adjustment is performed k_{pf} and T_A are decreased to $10\,\%$ of their nominal value, when temporary control is used. For scenarios with a high virtual impedance, an increase of k_{pf} by a factor of ten is also tested. P^* is set to zero. The scenarios are shown in table 2.

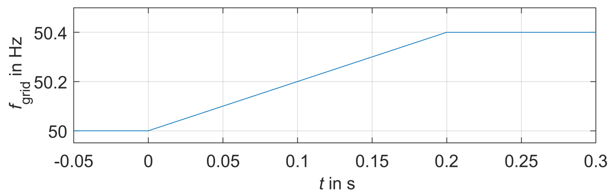

Fig. 5 Frequency of the external grid voltage in scenarios with rising grid frequency during fault

Table 2 Cases with parameter adjustments

Case	Parameter adjustment
a	$P^* = 0, T_A = 10, k_{pf} = 10$
b	$P^* = 0, T_A = 1, k_{pf} = 10$
c	$P^* = 0, T_A = 10, k_{pf} = 100$
d	$P^* = 0, T_A = 10, k_{pf} = 1$
e	$P^* = 0, T_A = 1, k_{pf} = 100$
f	$P^* = 0, T_A = 1, k_{pf} = 1$

An increased k_{pf} factor is not used when temporary current control is used, because the exact power setpoint adjustment suppresses frequency changes as long as the grid frequency is constant. When permanent current control is used, no parameter adjustments occur, because the VSM is deactivated.

3.2 Initial Situation

In order to show the challenges of grid-forming loads with regard to transient stability, a grid-forming load was exposed to a fault with a duration of $400\,\mathrm{ms}$. A high virtual impedance without setpoint adjustments is used in this scenario. During the fault, the inverter tries to reach its power setpoint by the reduction of its frequency. But due to the voltage sag, it can not be reached. This is shown in Figure 6. Associated with this the voltage support by the inverter is not good, because the voltage decreases over time. The fault is cleared too late for this inverter as the angle divergence exceeds $180°$.

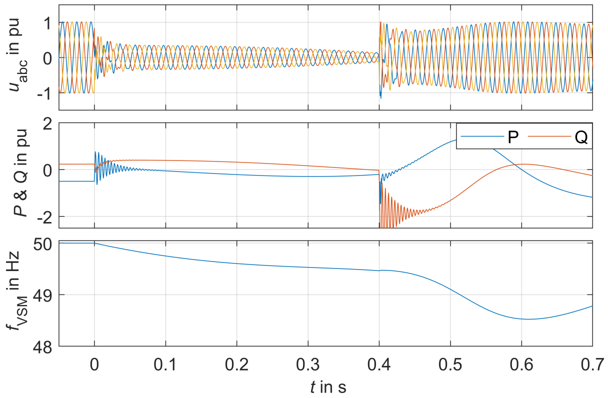

Fig. 6 Results of grid-forming load with high virtual impedance without adjustments - leading to loss of synchronism

3.3 Results with Permanent Current Control

In the following scenarios, current control is activated when a fault occurs and is kept activated during the fault. The VSM is re-initialized after fault clearing. In the first scenario, the grid frequency is kept constant. Afterwards, the results for a rising grid frequency are shown.

3.3.1 Constant Grid Frequency: In the moment the fault occurs and the voltage decreases, current control is activated, see Figure 7. The current control is able to limit the fault current and feeds in reactive power mainly. After fault clearing the pre-fault setpoints are used and a smooth transition back to grid-forming control can be observed. At fault clearing, a short-time exceeding of the current limit can be observed. This is due to the fact, that the current controller is not able to control the current exactly because of the disturbed voltage. The frequency of the VSM almost does not change, see Figure 8.

3.3.2 Rising Grid Frequency: In this scenario, the external grid frequency is increased during the fault, see Figure 5. The results depicted in Figure 9 are similar to the results with constant grid frequency, except for fault clearing. After the re-initialization of the VSM the power consumption increases due to the frequency droop of the VSM.

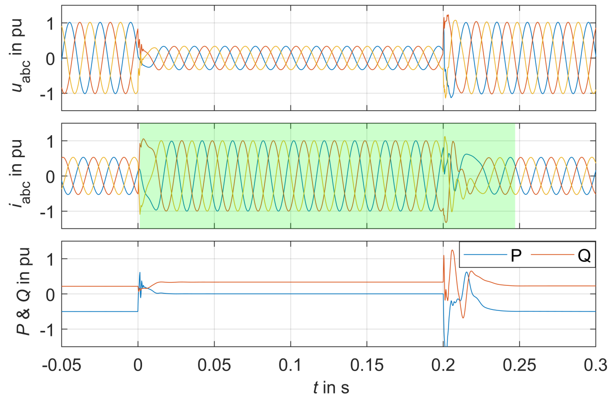

Fig. 7 Results of permanent current control and constant grid frequency; period of active current control highlighted in green

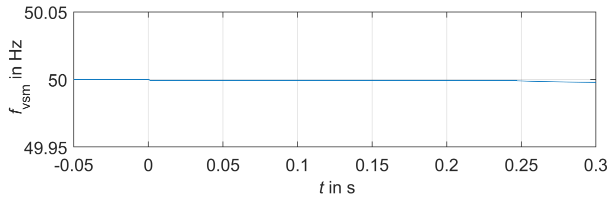

Fig. 8 VSM frequency under permanent current control and constant grid frequency

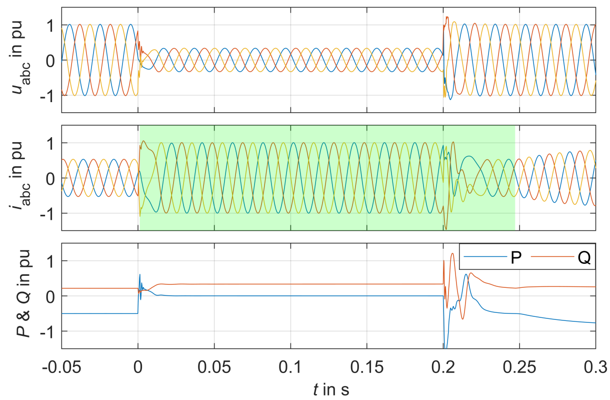

Fig. 9 Results of permanent current control and rising grid frequency; period of active current control highlighted in green

No frequency change can be observed during the fault in Figure 10. This is due to the fact, that the VSM reference is frozen. The constant feed-in of reactive power can be explained by the permanent calculation of the current setpoints, which are changing constantly in such scenarios. After fault clearing the inverter needs approximately $700\,\mathrm{ms}$ to reach the frequency of the external grid.

3.4 Results with High Virtual Impedance

For the following scenarios, the VSM with high virtual impedance is used and current control is always deactivated. Furthermore, the results with parameter adjustments of k_{pf}, P^* and T_A are shown.

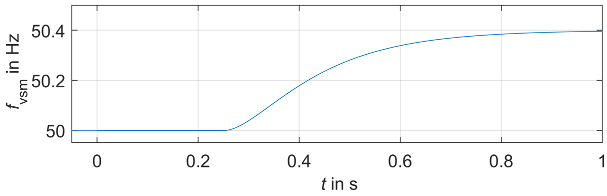

Fig. 10 VSM frequency under permanent current control and rising grid frequency

3.4.1 Constant Grid Frequency: The results for the VSM without parameter adjustments are shown in Figure 11. As expected the frequency decreases strongly during the fault because the VSM tries to reach the power setpoint but this is not possible due to the voltage sag and limited current. At fault clearing the current limit is exceeded, indicated by the power consumption.

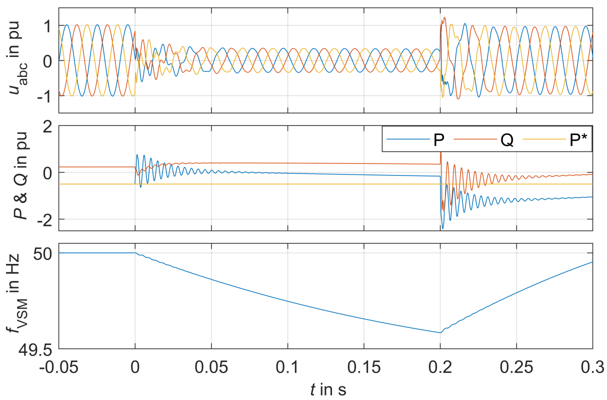

Fig. 11 Results with high virtual impedance without parameter adjustment and constant grid frequency for cases a-f

Adjusting the chosen VSM parameters changes the results drastically, see Figure 12. All adjustments lead to a lower frequency divergence compared to the stiff grid frequency.

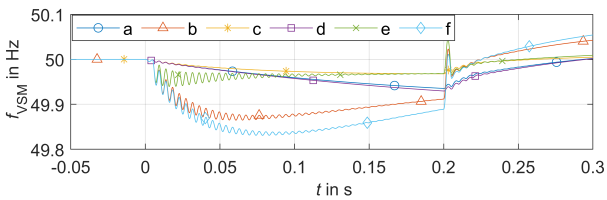

Fig. 12 VSM frequency with high virtual impedance, adjusted VSM parameters and constant grid frequency

The best results with regard to frequency change are obtained in case c and e. The reason for this is, that a high k_{pf} counteracts frequency changes. Despite the power setpoint adjustment, there is still an imbalance in power. This can be explained by the applied current limitation method. The power feed-in during the fault is not actively controlled like with current control. The power feed-in is a consequence of the power setpoint, virtual impedance, and the impedance seen by the inverter during fault. Setting P^* to zero is an assumption and does not necessarily reflect reality. Otherwise, no frequency changes would be visible either. The next best results are obtained in case a, where only the active power setpoint is adjusted. Similar results can be obtained by increasing k_{pf} and decreasing T_A, see case d. Case b and f perform worse, due to the fact that the inertia is decreased and k_{pf} is not strong enough.

3.4.2 Rising Grid Frequency: The results without adjustments and a rising grid frequency are quite similar to results with a constant grid frequency. The results are shown in Figure 13.

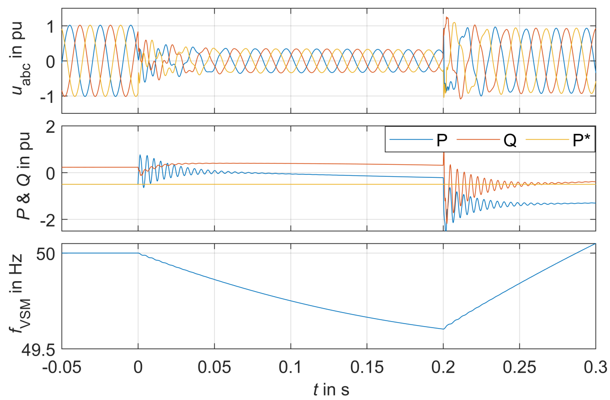

Fig. 13 Results with high virtual impedance without parameter adjustment and rising grid frequency

At the beginning of the fault, the results are similar to the previous results. But over time differences arise. At 0.2 s all cases reach coincidentally nearly the same frequency. As before, in cases with a high k_{pf} the inverter withstands frequency changes. Case b and f show a higher frequency deviation in the beginning but accelerate faster. This leads to higher frequency after fault clearing compared to the other cases. During a longer fault b and f would even show better results compared to the other parameter adjustments.

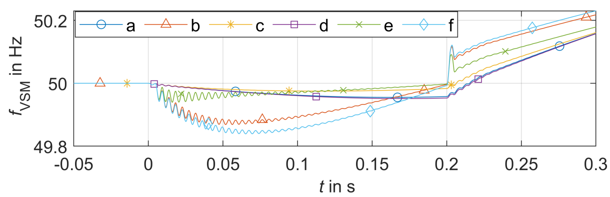

Fig. 14 VSM frequency with high virtual impedance, adjusted VSM parameters and rising grid frequency a-f

3.5 Results with Temporary Current Control

For the following scenarios, temporary current control is used. Also the results with parameter adjustments of k_{pf} and T_A are shown.

3.5.1 Constant Grid Frequency: Figure 15 shows the results when temporary current control is used. At fault beginning and fault clearing current control is active for a short period of time. Overcurrents are limited successfully. During the fault, the inverter mainly feeds in reactive power as intended. After fault clearing pre-fault active and reactive power are fed in.

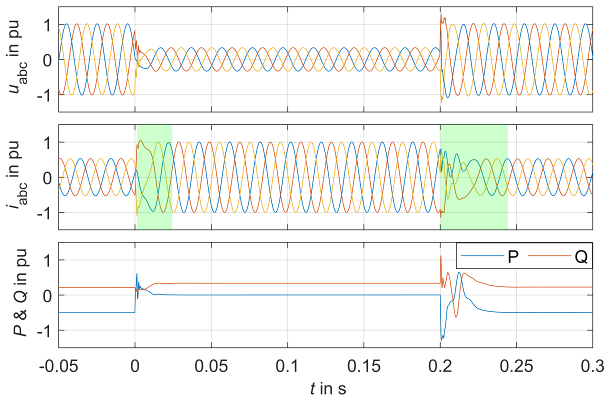

Fig. 15 Results of temporary current control and constant grid frequency; period of active current control highlighted in green

The VSM frequency is nearly unaffected by the fault and temporary current control, see Figure 16. This can be explained with a good re-initialization of the VSM and the adjustment of the active power setpoint. The results for parameter adjustment of k_{pf} and T_A are not shown, as no difference in the results can be observed. This is the consequence of the intended nonexisting power imbalance of the VSM achieved by temporary current control and the adjustment of P^*.

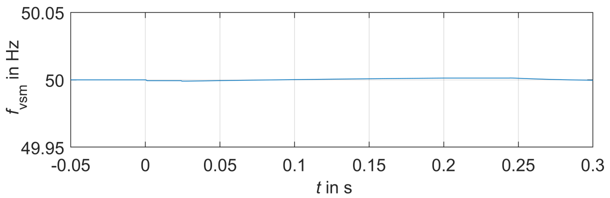

Fig. 16 VSM frequency under temporary current control and constant grid frequency

3.5.2 Rising Grid Frequency: In this scenario with rising grid frequency k_{pf} is decreased to $10\,\%$ of its nominal value and T_A were adjusted like before. In Figure 17 the different VSM frequency curves are shown. The result for not adjusted parameters is quite similar to the result with adjusted k_{pf}. A higher change of the VSM frequency can be observed when T_A is decreased. A simultaneously adjusted k_{pf} improves the result further. This can be explained by the fact, that the frequency droop does not counteract the frequency increase so much.

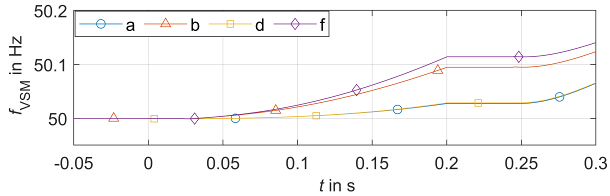

Fig. 17 VSM frequency under permanent current control and rising grid frequency; shown are results with normal parameters, adjustment of k_{pf}, T_A and k_{pf}&T_A

4 Discussion and Outlook

The behavior during fault of a grid-forming inverter coupling a load can be designed in the preferred manner as shown before. In a totally inverter-dominated grid, the obvious solution to address transient stability is to suppress frequency changes during fault. But parallel operation with synchronous generators must also be guaranteed in the future. The approaches shown should also be evaluated in a larger power system with varying penetration of inverters and synchronous generators. Furthermore, possible upcoming stability issues due to parameter adjustment have to be studied.

For grid-forming loads without an energy storage a control design is needed, which blocks power flows from the DC to the AC side. Otherwise, the DC voltage may fall below its allowable limit and the load has to be turned off. In this paper, the DC side was simplified and further research regarding other loads is needed.

5 Conclusion

Grid-forming loads can shorten the critical clearing time of a power system because the inverter frequency decreases during fault as a generator accelerates. Due to this, different methods for current limitation and adjustments of VSM parameters are proposed in order to change the frequency behavior during fault of a grid-forming load. Furthermore, it is shown how a constant or rising grid frequency during fault influences the inverter.

In case of a high virtual impedance for current limitation without any parameter adjustments, the VSM decelerates during fault. In the test system used, this is also the case when the external grid frequency increases. For parameter adjustment during fault the inertia of the VSM, the frequency droop, and the active power setpoint were chosen. A decreased power setpoint reduces the power imbalance and thus decreases the frequency change. A lowered inertia and smaller droop constant improve the ability of the inverter to follow the grid frequency. If the frequency should be kept constant a higher droop constant should be chosen. But even with adjusted parameters the VSM with high virtual impedance can hardly follow a rising grid frequency. Permanent current control keeps the VSM frequency constant but can not follow a rising grid frequency. In contrast to that, the use of temporary current control with smaller inertia and droop constant, allows the VSM to follow a rising grid frequency in the studied scenarios.

Acknowledgment

AGISTIN is supported by the European Union's Horizon Europe program under agreement 101096197. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

References

[1] A. Yazdani and R. Iravani, *Voltage-sourced converters in power systems: Modeling, control, and applications*. Hoboken, New Jersey and Piscataway, New Jersey: IEEE Press Wiley and IEEE Xplore, 2010.

[2] M. Ndreko, S. Rüberg, and W. Winter, "Grid forming control scheme for power systems with up to 100% power electronic interfaced generation: a case study on great britain test system," *IET Renewable Power Generation*, vol. 14, no. 8, pp. 1268–1281, 2020.

[3] J. Heid, W. Schittek, C. Hachmann, and M. Braun, *Asymmetric Contributions to Instantaneous Reserve by Generation, Loads, and Storage*. University of Kassel, 2022.

[4] H. B. Karadag, *CRITICAL CLEARING TIME IN GRIDS WITH VARIABLE PENETRATION OF GRID-FORMING CONVERTERS AND SYNCHRONOUS GENERATORS*. University of Kassel, 2023.

[5] C. Schöll and H. Lens, *Instability phenomena in interconnected power systems caused by current limitation of grid-forming converters*. 19th Wind Integration Workshop, 2020.

[6] D. Duckwitz, F. Welck, and C. Glöckler, "Operational behavior of the virtual synchronous machine," in *12. Fachtagung Netzregelung und Systemführung*. VDE Verlag, 2017.

[7] N. Wiese, D. Duckwitz, M. Nuschke, Y. Zhang, and M. Braun, *Fault operation of grid-forming converters with focus on system stability*. 11th Solar Integration Workshop, 2020.

[8] L. Huang, H. Xin, Z. Wang, L. Zhang, K. Wu, and J. Hu, "Transient stability analysis and control design of droop-controlled voltage source converters considering current limitation," *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 578–591, 2019.

[9] C. Luo, Y. Chen, Y. Xu, Z. Wang, and Q. Li, "Transient stability analysis and enhancement for vsg with virtual impedance based current limitation," in *IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society*. IEEE, 2022, pp. 1–6.

[10] Y. Lamrani, F. Colas, T. V. Cutsem, C. Cardozo, T. Prevost, and X. Guillaud, "A Comparative Study of Grid-Forming Controls and their Effects on Small-Signal Stability," 2023.

[11] D. Duckwitz, "Power system inertia: Derivation of requirements and comparison of inertia emulation methods for converter-based power plants," Ph.D. dissertation, University of Kassel, 2019.

[12] F. Welck, D. Duckwitz, and C. Gloeckler, *Influence of Virtual Impedance on Short Circuit Performance of Virtual Synchronous Machines in the 9-Bus System*. NEIS; Conference on Sustainable Energy Supply and Energy Storage Systems, 2017.

[13] N. Wiese, Y. Zhang, and M. Braun, *New current limiting control for grid-forming converter under unbalanced faults*. 21th Wind Integration Workshop, 2022.

[14] P. S. Kundur and O. P. Malik, *Power system stability and control*. McGraw-Hill Education, 2022.