Comparison of Selected Grid-Forming Converter Control Strategies for Use in Power Electronic Dominated Power Systems

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***Abstract* — Grid-forming converter control strategies have become an important alternative to classical synchronous machines in order to stabilise the power electronic (PE) dominated power systems. The paper compares selected grid-forming converter control strategies against each other and against state-of-the-art grid following control as well as against the behaviour of a synchronous generator and ideal voltage and current sources, by simulation test cases with small example networks. The main objective is to identify the core of grid-forming behaviour, by the same time to identify the mechanism that may inhibit stable operation of power systems with high PE penetration. The results underline the need of grid-forming controls in cases of PE dominated power systems and indicate that only the control designs which show a strong initial response within a quarter period following on changes in terminal voltage magnitude or phase angle can supply a power system with high penetration of PE in a satisfactory manner. A definition of grid-forming behaviour is introduced, and possible tests for grid-forming behaviour suggested.**

Keywords* — *Converter control, grid-following, grid-leading, grid-forming, virtual synchronous machine, droop control, direct voltage control, enhanced current control, power system stability, high penetration

I. Introduction

With increasing penetration of power electronic interfaced generating units in power systems, grid-forming converter control strategies have become an important alternative to classical synchronous machines in order to stabilise the power system in normal and disturbed operating conditions.

The state-of-the-art controllers used nowadays for grid-parallel operation of power electronic converters are grid-following, usually with inner loop current control in rotating reference frame and synchronised by a phase-locked loop (PLL). They cannot operate without an already existing grid voltage. In contrast, the island operation control nowadays is typically a V/f-control with constant frequency (constant voltage phase angle) adjusted by an oscillator. The V/f control forms the voltage of an island grid, but (without any further measures) it is not designed to run in parallel with other voltage-forming sources in large systems. Grid-forming control strategies combine characteristics of both, in order to form the voltage of a grid, while being able to synchronise and operate with other grid-forming units in a flexible manner. It is expected that with grid-forming control strategies, power systems of any size (from small island grids to larger interconnected power systems) can keep stable operation even with a high share of power electronic interfaced units up to 100%.

This paper describes briefly power electronic converter control strategies for grid-parallel and island operation, the behaviour of synchronous machines, as well as selected grid-forming converter control strategies, such as virtual synchronous machines (VSM), direct AC voltage control (DVC) and droop control. The paper elaborates especially on the understanding of characteristics within the short-term dynamic behaviour of generating units, which are essential to make a stable operation of a large power system possible.

For the analysis presented in the paper, the behaviours of the introduced control strategies are investigated by means of computer simulations and compared against each other. In addition, the behaviour of ideal sources, i.e. ideal voltage sources and current sources, is included into the comparison for a theoretical investigation.

Chapter II gives an overview of converter control strategies. The investigation for comparison of selected control strategies is described in Chapter III, results are presented and explained. Discussion of the results and conclusions are drawn in Chapter IV. Chapter V provides a future outlook.

II. Converter Control Strategies

In this chapter, an overview of typical and future-oriented control concepts for power electronic generating units (PE-GU) is given, as well as a classification or definition of the network behaviour is done: grid-following, grid-leading and grid-forming. In literature, grid-leading and grid-forming control concepts are sometimes also referred to as voltage-forming or voltage-injecting control concepts.

A. Grid-Following Converter Control

Grid-following control concepts are those, in which a synchronisation with the existing grid voltage and an injection of currents is executed in such a way that the angular position of the currents (active and reactive current components) follows the grid voltage. Nowadays, the state-of-the-art control concepts for grid parallel operation of PE-GU are grid-following.

Widely used is the regulation of the current with PI controllers in dq-components in the inner control loop (see for example [1]), which can be called voltage-oriented vector current control (DQCC). The synchronization with the terminal voltage takes place here with a phase-locked loop (PLL) [1].

In slower outer control loops active and reactive power and sometimes the voltage magnitude are regulated. In doing

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so, additional droops can be used to enable operational characteristics, such as Q(U) or P(f) characteristics. Voltage controls realised in this way respond relatively slowly. Only when detecting a network fault, the state-of-the-art controls activate a fault-ride-through (FRT) mode, in which the voltage is regulated with a fast proportional reactive current response in the outer loop, as required by most grid codes nowadays (e.g. [2]). By a slight enhancement of the control concept, such fast proportional voltage control in the outer loop can be enabled working in continuous operation (not state-of-the-art today). A frequency-sensitive mode (FSM) or limited frequency-sensitive mode (LFSM) as required by modern grid codes (e.g. [2]) can be added in the outer loop to adjust the setpoint of the outer loop active power controller.

B. Grid-Leading Converter Control (with fix frequency)

Grid-leading control concepts are those concept, which build the voltage thereby predetermine the voltage angle and keep the frequency fixed. This type of control is typically done in small island and offshore grids, in which the voltage is formed exclusively by one converter. Usually, a so-called V/f control is used, in which the voltage is regulated and the voltage angle or the frequency is given by an oscillator (see e.g. [3]). The V/f control is used e.g. in the offshore HVDC converter of HVDC connections to offshore wind farms. If additional converters are connected to the stand-alone grid (such as the wind turbines in an offshore wind farm), nowadays these converters are equipped with grid-following controls.

Since grid frequency is fixed when such control is used, it cannot be used to indicate power imbalances between generation and consumption, or to allow power distribution based on frequency deviation (P/f droops, primary control). In the case of frequency-fixed grids with grid-leading regulation, theoretically the power can be divided between several grid-leading converters by means of power/voltage angle droops or superordinate voltage angle regulations to implement a power system regulation, as outlined for example in [4][5][6][7].

The grid-leading V/f control concept can be enhanced by additional droop functions to a grid-forming droop control [3], compare Section II.C.2.

C. Grid-Forming Converter Control

Grid-forming control concepts can build the grid voltage and simultaneously synchronise with other converters or generators. Thus, they can work in parallel operation while building the grid voltage. Varies implementation concepts for grid-forming controls have been suggested by different authors in the recent years, such as virtual synchronous machines, droop control, direct voltage control or enhanced current control. Those are briefly explained in the following subsections.

ENTSO-E divides power park modules into three classes, from which Class 1 (in future renamed to Class 3) can be understood as grid-forming, because it includes requirements which mean a grid-forming behaviour in its consequence (namely to create system voltage, to contribute to inertia and to support first cycle survival) [8]. Further requirements for Class 1 are to contribute to fault level, to act as sink for harmonics and unbalances and to prevent adverse controller interactions.

1) Virtual Synchronous Machines

Typical representatives of grid-forming control concepts are virtual synchronous machines (VSM), in which equations are implemented in the control that partially or completely emulate the behaviour of a synchronous machine (see for example the virtual synchronous machine “VISMA” [9][10], or the “synchronverter”[11][12]).

Virtual synchronous machines reproduce the physical behaviour of real synchronous machines including their advantageous grid-forming capability. Depending on the implementation however, the disadvantages of the synchronous machine can be included in the VSM as well, namely their ability of oscillations which can lead to oscillatory instability in the event of insufficient damping, and the risk of losing the transient stability.

2) Droop Control in the Inner Control Loop

For use in stand-alone grids and microgrids, recently droops have been established in the inner loop, enhancing the otherwise rigid V/f control by f/P and V/Q characteristics. By means of the droop functions, a common operating point is established by parallel converters and thus a “multi-master” operation is possible [13]. In some publications, such droop control concepts are also referred to as virtual synchronous machines without inertia (VSM0H, e.g. [14]). Applications in photovoltaic diesel hybrid diesel networks on islands have already been successfully implemented in practice (e.g. [15][16]).

3) Direct Voltage Control

The Direct Voltage Control (DVC) represents a further development of the proven grid-following voltage-oriented vector current control towards a grid-forming control [17][18][19][20][21]. The direct voltage control is not to be mistaken for the dc voltage control of a voltage source converter (VSC) or the direct modulation regulation of a modular multi-level converter (MMC). The main features of the DVC are [19]:

- A separation is made between the slow reactive power control in the outer control loop and a downstream, fast proportional voltage control.
- Fast voltage regulation is carried out continuously and without dead-band, both in normal operation and in the event of fault.
- The integrators in the inner loop are removed, i.e. there is no current control with PI controllers.
- Without the integrators in the inner control loop, reactive current (for voltage control) and active current are not fixed, but result from the voltage difference between the controlled inverter voltage and the terminal voltage (or the grid impedance).
- The active current or the active power is mainly controlled by the q component of the inverter voltage, and thus by the angle between the inverter voltage and the terminal voltage.

4) Enhanced Current Control

In this concept, the DQCC converter concept is extended by adding a df/dt control (synthetic inertia, SI) in the outer control loop and realising a continuous proportional voltage control in the outer control loop [22][23].

III. INVESTIGATION

A comparative investigation with selected converter control strategies is provided in this chapter. The converter responses are compared against each other and against the response of a synchronous generator, which is equipped with an automatic voltage regulator (AVR) and governor (speed/power controller). In the first test cases the responses of an ideal uncontrolled voltage source and an ideal uncontrolled current source are presented as well as reference. The investigation is done by means of EMT simulations in DIgSILENT PowerFactory Version 2019. The curves in the plots show magnitudes of space phasors, instantaneous power and instantaneous reactive power, which in steady-state conditions are identical to RMS quantities, active and reactive power.

Four test cases are presented in the paper:

A. Response on step in voltage magnitude in a single machine at infinite bus system

B. Response on step in voltage phase angle in a single machine at infinite bus system

C. Response on load change in a two machine system with 50% PE-GU

D. Response on load change in a two machine system with 100% PE-GU

For the device under test (DUT), the following is used:

- Ideal uncontrolled voltage source (only test A and B)
- Ideal uncontrolled current source (only test A and B)
- Synchronous generator (SG), as a reference
- PE-GU with DQCC in the inner control loop, P and Q control in the outer control loop (PI controllers)
- PE-GU with DQCC in the inner control loop, P and V control in the outer control loop (PI controllers)
- PE-GU with DQCC in the inner control loop, P and V control in the outer control loop (PI controllers), plus FSM for adaption of the active power setpoint
- PE-GU with DQCC in the inner control loop, P control in the outer control loop (PI controller), plus FSM, continuously acting fast proportional voltage control in the outer loop (cascade of slow PI controller and fast proportional control)
- PE-GU with DQCC in the inner control loop, P control in the outer control loop (PI controller) plus FSM and fast acting synthetic inertia, continuously acting fast proportional voltage control in the outer loop; this corresponds to the Enhanced Current Control
- PE-GU with Direct Voltage Control (DVC)
- PE-GU with Droop Control (f/P and V/Q droops), without PLL
- PE-GU with VSM similar to a synchronverter implementation without PLL

A. *Response on Step in Voltage Magnitude*

The DUT is connected to a Thevenin equivalent (voltage source with impedance) via a transformer, see Figure 1. The Thevenin equivalent is a simplified network representation.

The voltage magnitude of the Thevenin's voltage source is decreased by 1% at t = 0.0 s. The responses of the individual DUTs are shown in Figure 2 through Figure 4. The figures show results in p.u. based on nominal voltage, rated current and MVA rating of the DUT respectively.

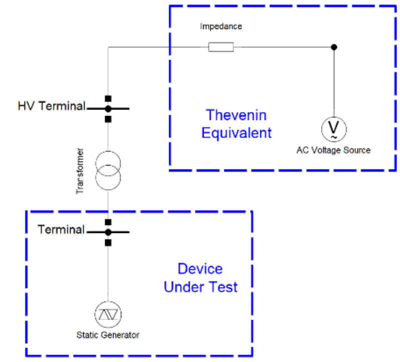

Figure 1: Single-line diagram of the first test case

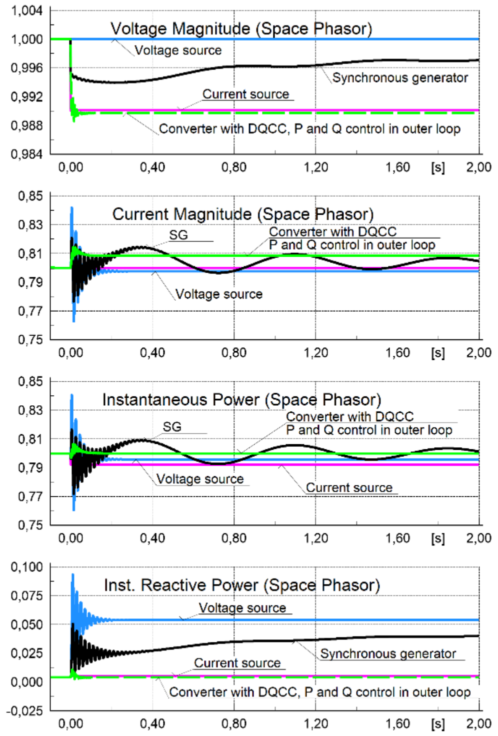

Figure 2: Response of DUT on voltage magnitude step

The voltage source (Figure 2, light blue) and the SG (Figure 2, black) show a strong initial response in the current and powers respectively. The ripple in the space phasor magnitude is caused by the DC components which occur with different magnitudes in the phase currents, because of the inductances in the network. The voltage source produces additional reactive current while keeping the voltage magnitude constant. The SG's voltage regulator (AVR) increases the reactive power slowly to maintain the voltage. In contrast, the current source (Figure 2, pink) keeps its current constant and does not support voltage. Because of constant current at lower voltage, the power injected by the current source is reduced after the voltage step. The converter with DQCC and power control (Figure 2, light green) keeps its power constant. For achieving this, it increases current output, but does not support the voltage magnitude.

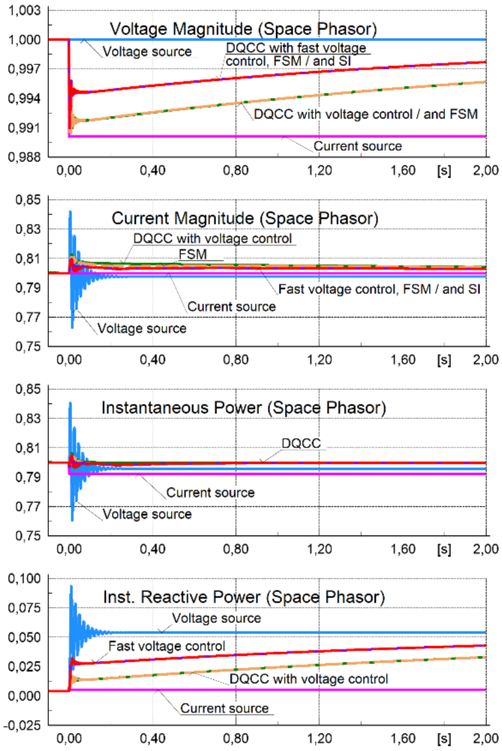

Figure 3: Response of DUT on voltage magnitude step

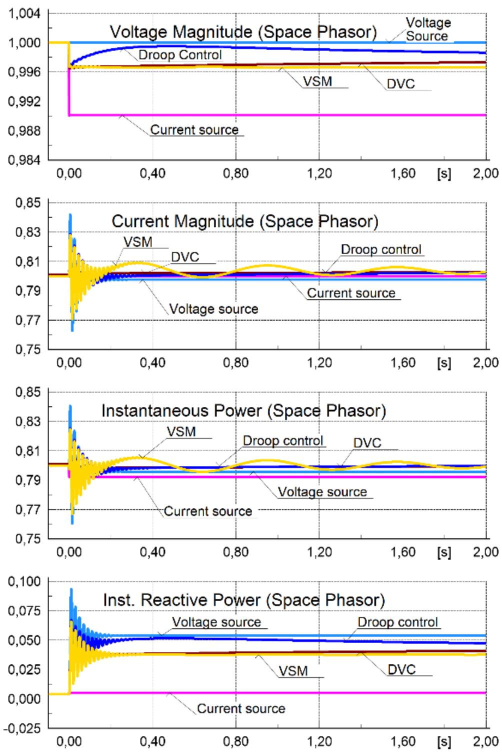

Figure 4: Response of DUT on voltage magnitude step

By replacing the reactive power control with a voltage controller in the outer loop of the PE-GU DQCC, the response is improved with respect to voltage support. The initial response is just marginal, but reactive power is increased in the following seconds (Figure 3, dark green curve). An additional FSM does not impact the result in this test case (Figure 3, orange). Establishing a continuously acting fast proportional voltage control in the outer loop improves the voltage support further (Figure 3, purple), an initial response in the instantaneous reactive power becomes notable within the first quarter period. An additional SI does not have an impact in this test case (Figure 3, red).

DVC (Figure 4, brown), VSM and droop control show a fast and strong response (starting within the first quarter period following the voltage change). The VSM tends to oscillate slowly similar to the SG, because of its internal inertia emulation (Figure 4, yellow). The behaviour with droop control (Figure 4, blue) is close to that of the ideal voltage source.

B. Response on Step in Voltage Phase Angle

The DUT is connected to the same Thevenin equivalent (voltage source with impedance) via a transformer as in test case A. The voltage phase angle of the Thevenin's voltage source is changed by 1.0° at t = 0.0 s.

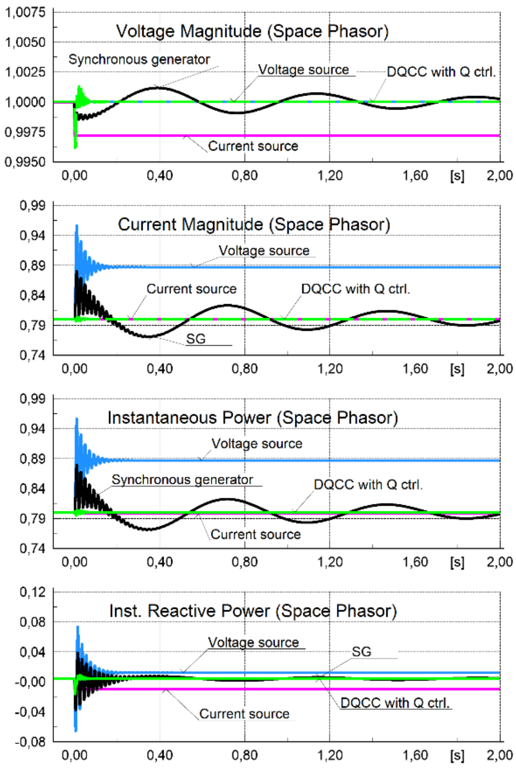

Figure 5: Response of DUT on voltage phase angle step (instantaneous power plot replaced by correct plot)

Again, the voltage source and the SG show a strong initial response (Figure 5, light blue and black). The current source keeps its current magnitude constant and thus reacts on the phase angle step by changes in power which do not support the grid (the reactive power changes in the opposite direction then the reactive power of the voltage source, Figure 5, pink). The PE-GU with DQCC and PQ control in the outer loop shows just a marginal transient and then keeps the power constant (Figure 5, light green).

FSM and fast acting voltage control in the outer loop do not show an effect (see Figure 6, orange and purple). The SI causes a small initial response (Figure 6, red).

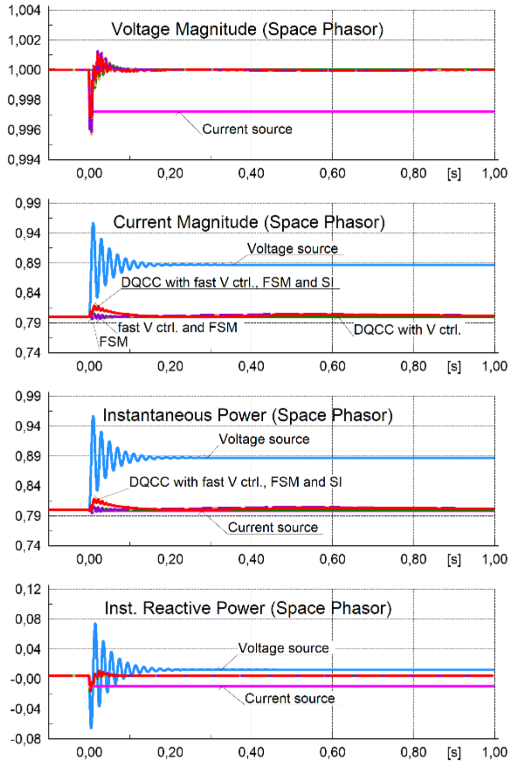

Figure 6: Response of DUT on voltage phase angle step

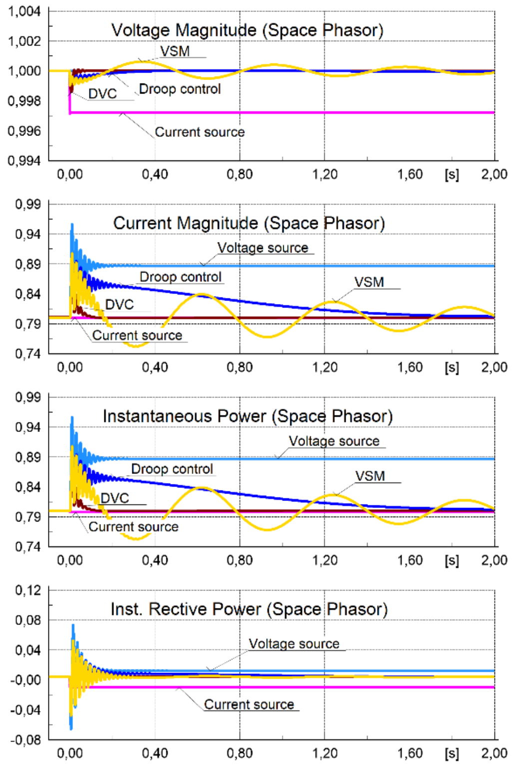

Figure 7: Response of DUT on voltage phase angle step

The DVC shows an initial response of medium magnitude (Figure 7, brown). Again, VSM and droop control show a fast and strong reaction. The response of the VSM (Figure 7, yellow) is similar to that of the SG with damped low frequency oscillations. The behaviour of the droop control (Figure 7, blue) is closer to that of a voltage source.

Because the frequency in the test system is kept constant by the Thevenin equivalent, the power output of all realistic DUTs turns back to their pre-event value. Only the ideal uncontrolled sources do not adjust their power output.

C. Operation in Parallel with Synchronous Generators, Response on Load Change

This investigation is done using a two machine test case: A SG and the device under test (DUT) have the same rating and supply a load. “Load 1” is modelled as a constant power load. At t = 0 s the load is increased by 1% by switching on an impedance based load (“Load 2”).

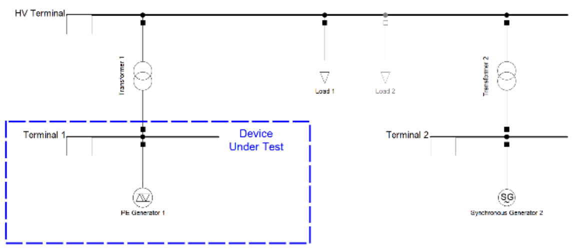

Figure 8: Single-line diagram of the two machine test case

The following figures depict the results for the total power generation (sum of instantaneous power of all generating units in p.u. based on installed generation MVA capacity), the voltage magnitude (in p.u. based on nominal voltage) and frequency (in Hz) at the load bus, the injected instantaneous power and the instantaneous reactive power of the DUT (in p.u. based on rated MVA of the DUT). The instantaneous power is calculated from the space phasor quantities. In steady-state the instantaneous power corresponds to active power and the instantaneous reactive power corresponds to reactive power.

Figure 9 and Figure 10 show the behaviour of the SG and the PE-GUs using different control strategies. In all cases, a frequency drop is observed after the transients have decayed. The black curve corresponds to the case in which the DUT is a SG. In this situation, the two SGs share evenly the load change. For the PE-GU cases, it can be seen that all control strategies except the DQCC with Q control have a final steady-state contribution to either the additional active or reactive power or both. DQCC with V control provides a response to the increase of reactive power demand whereas the active power output remains almost constant during the event in both transient and steady state time frames. If observing the transient behaviour, then the FSM and the fast voltage control do not have substantial instantaneous response in active power. This is due to fact that the current control loops ensure that the active current is steadily increased thus avoiding the initial current “kick”. The response in this situation is highly dependent on the selection of the inner control loop parameters, as will be highlighted in the next test case. With respect to the steady state response, the FSM and the fast voltage control respond adequately to the load change, sharing the load mismatch with the SG.

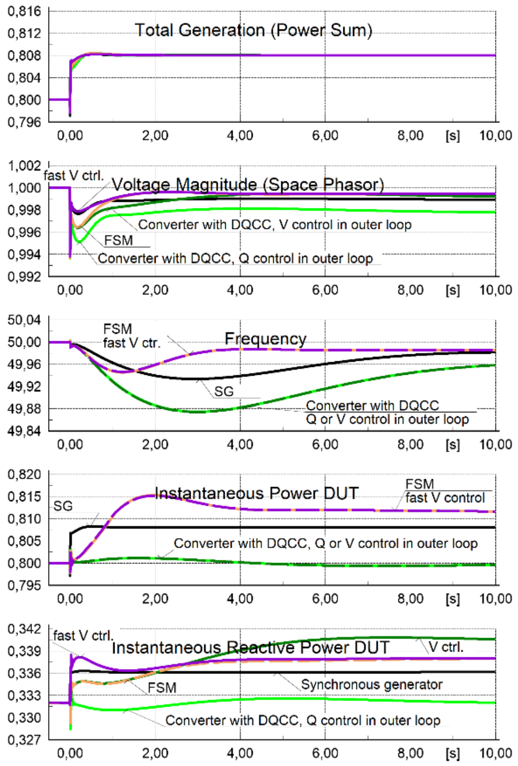

Figure 9: Response on load change, 50% PE

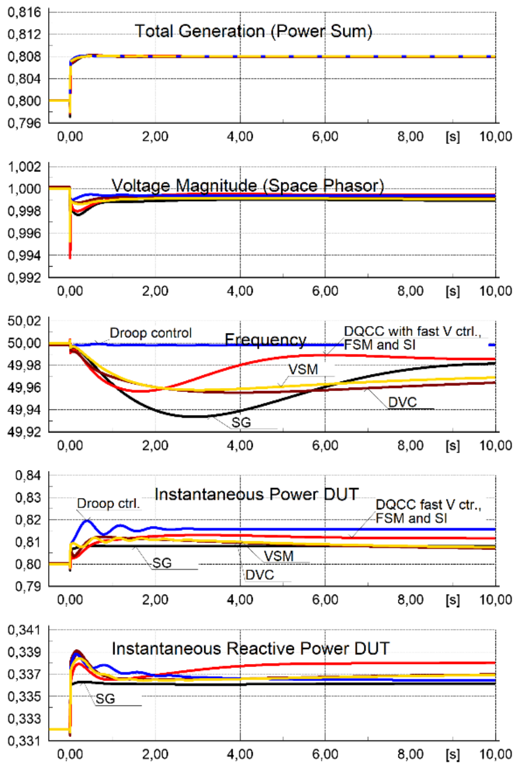

Figure 10: Response on load change, 50% PE

Within Figure 10, the load change scenario with a 50% PE penetration is applied to the Droop control (blue), VSM (yellow), DQCC with fast voltage control with FSM and SI (red) and the DVC (brown) control concepts. All these control methods provide responses in active and reactive power in both the short-term and the steady-state time frames. The DQCC with fast voltage control, FSM and SI provides good response within the steady state range; compared to the DQCC without SI, the active power response is improved by employing the fast reacting SI in the transient period. The VSM and the DVC perform similarly to each other, both outperforming the SG in terms of maximum frequency deviation. It is noted that further parameter tuning can still be made in order to closely match the performance of the SG (e.g. inertia, damping parameters). The droop control seems to perform well, although it is noted that the droop coefficients were set in a way that results in a large share of active power taken by the PE-GU with droop control, resulting in a small frequency deviation following the load step. Figure 11 shows the frequency of the droop control in more detail, together with the speed of the parallel synchronous generator. Both respond reasonable and in a stable manner. The frequency of the power system is dominated by the droop control, with the SG oscillating against it.

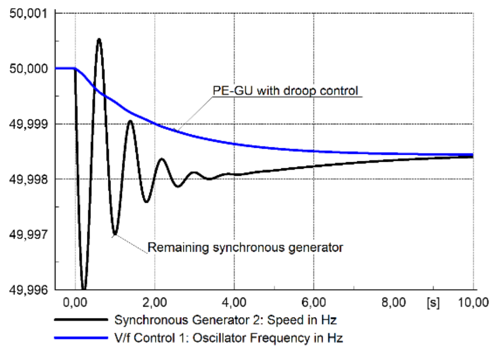

Figure 11: Response in frequency of PE-GU with droop control and of remaining SG on load change; 50% PE

D. Operation without Synchronous Generators, Response on Load Change

The test case is enhanced by exchanging the synchronous generator by a second DUT. Now the grid is supplied to 100% by PE-GU.

The results obtained with DQCC based control concepts having a typical parameterization do not show a stable response (Figure 12). Following the load change, the quantities start to oscillate within a period in an un-damped manner. Special attention should be drawn to the instantaneous power curves: It is expected that a stable power system supplies the load demand instantaneously. The synchronous generator takes the load demand within the first quarter period (a faster response is not possible, because the current oscillates with fundamental frequency and cannot jump within an inductive path in the power system). The converters with DQCC do not have a relevant response in the first quarter period, it is suppressed by the fast DQCC. Their instantaneous power is increasing too late, resulting in unstable oscillations. We may say that with typically parameterised DQCC there is not sufficient synchronizing torque within the power system.

By desensitising the inner current control loop, i.e. reducing the gains of the DQCC and by this making it slower, a stable behaviour is obtained within the short-term transient time frame. As such, within Figure 13, the load change scenario with a 100% PE penetration is applied to PE-GU with DQCC with P and Q control (light green), DQCC with P and V control (dark green), DQCC with P and V control and with FSM (orange), and DQCC with fast voltage control in the outer loop and FSM (purple). With slow DQCC, a fast response in instantaneous power and instantaneous reactive power following the load change is made possible (the response is notable within the first quarter period). It is nevertheless observed that, although stable within short term, the DQCC-PQ, DQCC-PV and DQCC-FSM are unable to recover in the long term to a stable operating point. The DQCC with fast voltage control and FSM is the only one PE-GU concept depicted in Figure 13, that is able to ride through the transient and continue stable operation.

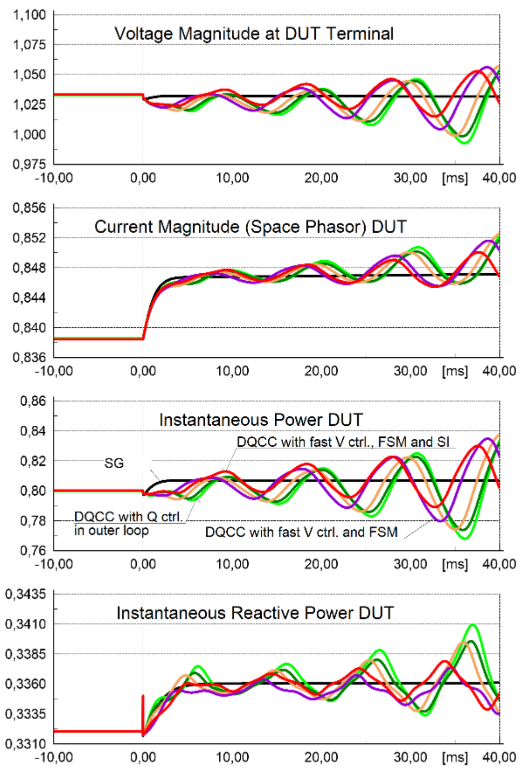

Figure 12: Response on load change, 100% PE with fast DCQQ (i.e. typical parameterisation), 100% SG for comparison

Figure 14 shows the response of ~~Figure 10~~the droop control (blue), VSM (yellow), DQCC with fast voltage control, FSM and SI (red) and the DVC (brown) control concepts. All these control methods provide stable operation in both the short-term and the steady-state time frames (the change in voltage magnitude at 8 s in the case of DVC is still under investigation, but expected to be controllable). The control concept of DQCC with vast voltage control, FSM and SI provides a better damping of the slow power oscillation compared to the DQCC with vast voltage control and FSM without SI (compare Figure 13, purple, with Figure 14, red).

Figure 15 zooms into the first two periods following the load change. The initial responses of the depicted control methods (with respect to current magnitude, instantaneous power and instantaneous reactive power) are almost identical and settle within the first quarter period. This initial behaviour is mandatory to survive the load change in the first period and to make sufficient action of slower controllers possible in the subsequent time frames.

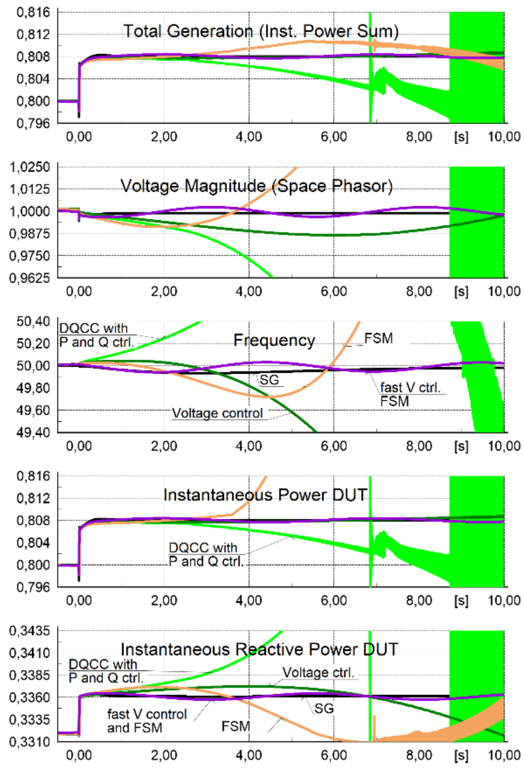

Figure 13: Response on load change, 100% PE with slow DCQQ (100% SG for comparison)

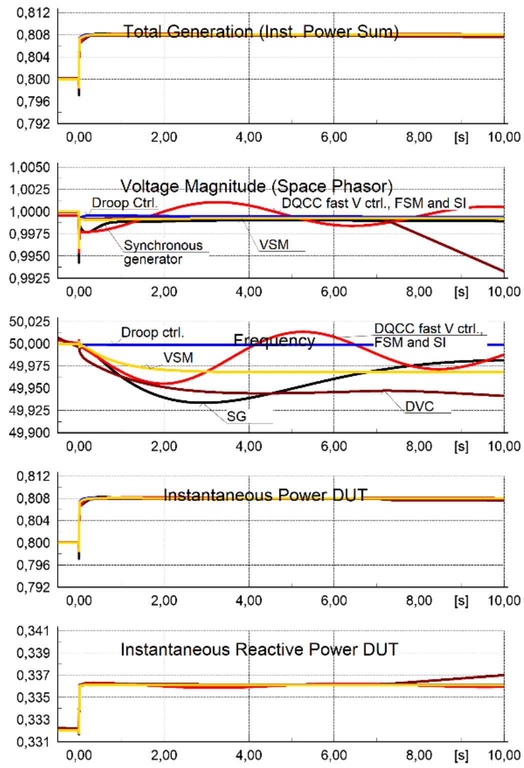

Figure 14: Response on load change, 100% PE (100% SG for comparison) (result of DQCC with fast V ctrl., FSM and SI improved)

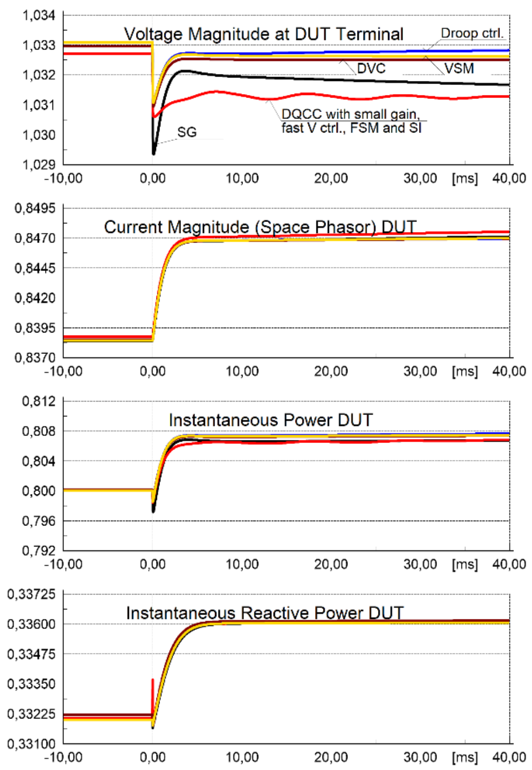

Figure 15: Response in first two periods following on load change, 100% PE (100% SG for comparison) (result of DQCC with fast V ctrl., FSM and SI improved)

IV. Discussion of Results and Conclusions

The analysis presented in the paper focuses on selected grid-forming converter control strategies for use in PE dominated power systems. State-of-the-art control strategies, namely DQCC with different control options in the outer loop have been included in the investigation as well. The main objective has been to identify the core of grid-forming behaviour, by the same time to identify the "killing mechanism" that may inhibit stable operation of power systems with high PE penetration.

The results indicate that only the control designs of PE-GU which show a strong initial response on changes in terminal voltage magnitude and phase angle can supply the system with high penetration of PE in a satisfactory manner. Without sufficient response of generating units in instantaneous power and instantaneous reactive power within the first quarter period, the power system is not able to survive the first period following a load change. DQCC with typical parameterisation does not show such initial response. Voltage and frequency regulation in the outer control loop in conjunction with typically parameterised DQCC are too slow to keep the system stable. However, the test case results have shown that DQCC tuned to be slow (small controller gains) with fast proportional voltage control, FSM and SI is able to ensure continuous stable operation of a grid with high PE penetration. In comparison, VSM and droop control in the inner loop show a more effective behaviour, are less sensitive to events in high PE penetration cases and seem to be easier to tune to ensure stable operation, which is probably preferred in a high PE penetration scenario, especially in smaller power systems (island systems, microgrids). However, it should be noted that the control parameter values must be selected with care with all controller methods, in order to enable stable operation while running in parallel to SGs or to other PE-GUs.

All adaptions of controllers and all control concepts which result in sufficient response within the first quarter period, have made the power system to survive within the first periods (while all others have not). Based on this analysis, the following definition of the core of grid-forming behaviour can be introduced:

Definition of grid-forming behaviour: A generating unit is called being *grid-forming*, if its output space phasor power shows a substantial, initial response within a quarter period on any changes in voltage magnitude as well as on any changes in voltage phase angle, with the net effect of counteracting those changes.

Grid-forming by this definition refers to the ability to stabilise the power system in the very short-term. Further control functions are usually required to ensure subsequent stable grid operation (e.g. power/frequency and voltage controllers).

By intention, the above definition does not refer to a "voltage source behaviour", because even a synchronous machine (which is believed to be grid-forming) does not respond fully equally to an ideal voltage source. Further, the definition does not exclude DQCC in the inner control loop, as long as it is parameterised (and enhanced by outer loop controls) to fulfil the required objectives. It should be noted, that in cases of PE-GU it is not only the control structure, that may produce grid-forming behaviour, but also the parameterisation of the controller. It should further be noted, that grid-forming behaviour alone does not ensure stable power system operation; subsequent (slower) control actions are needed in addition to ensure fulfilment of the classical voltage and frequency stability of the power system (and transient stability in cases of SG) and power balance in steady-state.

Testing of grid-forming capability can be done by applying steps in voltage magnitude as well as in voltage phase angle at the DUT's terminal, similar to the test cases described in Section III.A and III.B. A step in voltage magnitude should result in an initial response (within a quarter period) in instantaneous reactive power, while a step in voltage phase angle should result in an initial response (within a quarter period) in instantaneous ~~reactive~~ power, to prove grid-forming behaviour.

The paper focuses on the behaviour of generating units, considering the power system load being mainly a constant power load, because a controlled load behaviour is assumed. In general, the power system load is changing along with the power generation towards a PE dominated system and as such, the load behaviour has a fair influence on the power system's behaviour as well. For simulations including high PE penetration scenarios, the correct representation of loads must be considered with the same importance as the accurate modelling of generating units.

V. Outlook

Although being of fundamental general nature, the analysis has just covered a limited range of possible network disturbances and aspects in PE-GU behaviour. Future work is needed to enlarge the comparison of grid-forming control behaviour in a holistic approach and to prove their suitability for use in PE-dominated power systems. As such, further investigations of the behaviour in cases of short-circuits, and with larger network models are pursued. Comparison with phasor-based RMS simulation results are needed, as this is the tool of choice for large-scale disturbances on larger power systems. Eigenvalue analysis will complete the investigation to identify possible weakly damped modes (important for improving controller parameterisation and to ensure power system small signal stability).

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