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Flexible parameterizable grid-forming converter control by separated fast synchronization and slow inertia response control loops of Direct Voltage Control

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Abstract: As power systems, transit to a state of high renewable penetration with predominant converter-based grid interface instead of synchronous generators applied by conventional power plants, the dynamics of the grid significantly change, causing new challenges for transmission system operations and arising new opportunities, as converter-based generation is highly controllable in faster timescales. This paper discusses the extension of the direct voltage control as 'a decoupled grid forming converter controller', which effectively relies on an accurate and fast d/q-reference frame determination to control the frequency as well as its rate of change at the common coupling point with the grid. The proposed controller separates the task of synchronizing the converter to the grid and providing virtual inertia into two distinct control functions, which enables a specific tuning of both functions for their task avoiding the necessity to find any kind of trade-off between quality of synchronization and inertia provision. The functionality of the proposed control is explained and demonstrated via EMT-Type simulations in different study cases for system-spilt, islanding, and re-synchronization scenarios.

Keywords: grid forming inverter, direct voltage control, frequency response, nadir, rate of change of frequency (RoCoF).

1. INTRODUCTION

A major technical challenge of the energy transition is the change in generation technology: from synchronous machines and their well-known dynamics and controllers to power electronics-interfaced generation, whose regulation and interaction with the rest of the system are yet to be fully understood [Milano et al. (2018)]. One of the major consequences of this transition towards a nearly 100% renewable system is the gradual loss of synchronous generators (SG) with their inertia and control mechanisms [Rosso. R et al (2021)]. This loss of rotational inertia changes the nature of the power system to a low-inertia network resulting in critical stability challenges. On the other hand, renewable generation interfaced by power converters allows frequency and voltage control at much faster time scales compared to SGs [Tayyebi. A, et al (2021)].

Indeed, power converters are already starting to provide new ancillary services, modifying their active and reactive power output based on local measurements of frequency and voltage. However, because of the dependency on frequency measurements, these grid-following control techniques only replicate the instantaneous inertial response of SGs after a contingency with a delay and result in degraded performance on the transient time scales of interest [Y. Li et al (2021)]. To resolve this issue, grid forming converters (GFCs) are envisioned to be the cornerstone of future power systems. Based on the properties and functions of SGs, it is expected that GFCs must support load-sharing/drooping, black-start, inertial response, dynamic voltage support, and hierarchical frequency/voltage regulation. Moreover, a long transition phase is expected, where SGs and GFCs must be able to interact positively and ensure system stability.

The main features of a GFC control are voltage source behavior and power-based synchronization. Different techniques have been investigated for GFC control which can be classified into five major GFC strategies, namely: 1) droop control, 2) synchronverter, 3) matching control, 4) virtual oscillator control (VOC) and 5) IoT/ICT based approaches [Tayyebi. A et al (2018)]. These control methods have already shown good results in various publications. The major drawback of most GFC types is the coupled active and reactive power control as well as their corresponding currents.

Direct voltage control (DVC) is mainly a partial GFC control scheme in d/q reference frame, which has achieved good simulation results in various applications, such as stabilizing the grid voltage of an offshore wind farm in case of sudden blocking of the HVDC offshore converter [Erlich. I et al (2017); Neumann. T et al (2015); Korai. A et al (2017)].

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Recently, DVC is developed to fully GFC, which is synchronized using a swing equation, which is driven by Newtonian physics by mapping second-order frequency trajectories following power imbalances [Denecke. J et al (2021)].
In the fully GFC- DVC, the synchronization swing equation is mainly intended to serve the purpose of power-based synchronization with a high damping factor to impact rapidly, causeing kill inertia. Because of the fast nature of the synchronization control loop, to provide an actual angle input for the d/q reference frame, frequency control and virtual inertia functions are better to be taken over by other controller components separately.
This paper proposes a controller, which splits the task of synchronizing the converter to the grid and providing virtual inertia into two separate control functions. The first control function is tuned for fast synchronization to ensure fast and accurate decoupled control of active and reactive power in a d/q frame and the second one can be adjusted to improve the inertial response of the power system. Both functions are realized as swing equations called fast swing equation for synchronization and slow swing equation for provision of inertia with a different mechanical time constant T_a (corresponding to acceleration unit constant or 2H in a traditional SG).

The functionality of this new approach for DVC is examined and compared with conventional generators as well as ordinary fully GFC- DVC (with only synchronization swing equation) in the case of the primary control response, RoCoF, and nadir of the test system regarding the additional load corresponding to the sudden loss of generation. Furthermore, severer disturbances like system split, islanding operation as well as re-synchronization are tested to prove the capability of 100% converter-base generation as well as overall frequency stability.

The paper is organized as follows. Section 2 presents GFC-DVC. The proposed control strategy of separated RoCoF and synchronization to regulate both the frequency and the RoCoF at the point of common coupling (PCC) is presented in Section 3. Section 4 shows the functionality of the proposed controller via the simulation results in Matlab/ Simulink. Finally, Section 5 draws conclusions and future work directions.

2. DIRECT VOLTAGE CONTROL

2.1. DVC as Line Side Converter (LSC) Control

For this paper, the DVC is implemented as a LSC control of a full converter according to fig. 1, which is fed from a DC link. The virtual mechanical power p_{mec} (fig. 2) represents the reference of the active power so that the balancing of the DC-link voltage is the responsibility of a PI-controller 'controlled current source'. The parameters of the PI controller correspond to typical values to approximate realistic DC-link dynamics. From fig. 1, the output voltage $\underline{u}_C = u_{C,d} + ju_{C,q}$ of the DVC controlled inverter in d/q frame oriented to u_{Line} drives from the Kirchhoff equation:

$$u_{C,d} = u_{Line} - xi_{q,ref} \qquad u_{C,q} = xi_{d,ref} \tag{1}$$

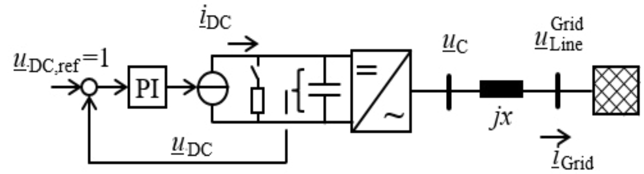

Fig. 1. Simplified electrical design DVC

The control is performed in a d/q-frame-system with the appropriate angle, which is described in detail as follows. The internal current references of the control $i_{d,ref}$ and $i_{q,ref}$ are formed from the virtual mechanical power p_m of the swing equation and a reactive power reference q_{ref} (fig.2).

$$p_e = u_{Line}.i_{d,ref} \qquad q_e = -u_{Line}.i_{q,ref} \tag{2}$$

2.2. DVC structure

The main features of a GFC control are voltage source behavior and power-based synchronization (PBS). Voltage source behavior has already been demonstrated by DVC in various works [Erlich. I et al (2017); Neumann. T et al (2015); Korai. A et al (2017)]. DVC is synchronized to the grid based on voltage or active power balancing. Synchronization of DVC based on grid voltage using fundamental frequency detection is called "partial GFC-DVC". If synchronization is done using a swing equation, is called "fully GFC-DVC".

The principle idea of the DVC is that the output voltage of the converter is controlled directly and not indirectly via current controllers. It resembles classical converter controls in rotating d/q-coordinates, that have the same outer loop controller, but avoids the use of the integral component of the proportional-integral (PI) current controllers and shifts the proportional component towards the output terminal, for the inner loop controller, which gives the DVC a voltage source behavior instead of a previously current source behavior. To limit the effect of this part (proportional component) on the dynamic behavior, this component uses a high-pass washout filter (HP) in this approach. The main control task is done by the feed-forward terms u_{Line}, which are sufficient because there are already integral controllers in outer loop controllers for the active current and the reactive current (fig. 2). This similarity to classical inverter control offers the advantage that many well-known principles from classical inverter control can be applied to DVC, so DVC is not a completely new technology with its associated uncertainties.

Furthermore, the use of d/q-coordinates in control has several advantages over polar coordinates, which are used in some other GFC control schemes. These advantages include decoupled control of active and reactive power, and the fact that with DVC the converter output voltage can be formed directly from the internal current references as well as the measured grid voltage via Kirchhoff equations mentioned in eq (1).

Fast voltage control according to actual requirements of network codes is provided by the factor k_u in the d-axis of the DVC (fig. 3) which depends on strength of grid connection and would be decided by the network operator in the process of grid integration. This fast voltage control responds to voltage changes in the opposite direction in the inverter output voltage. The low-pass filter (LP) in this branch delays this control function to decouple the response of this function in time from the inertial response of the synchronizing swing equation or to avoid their superposition.

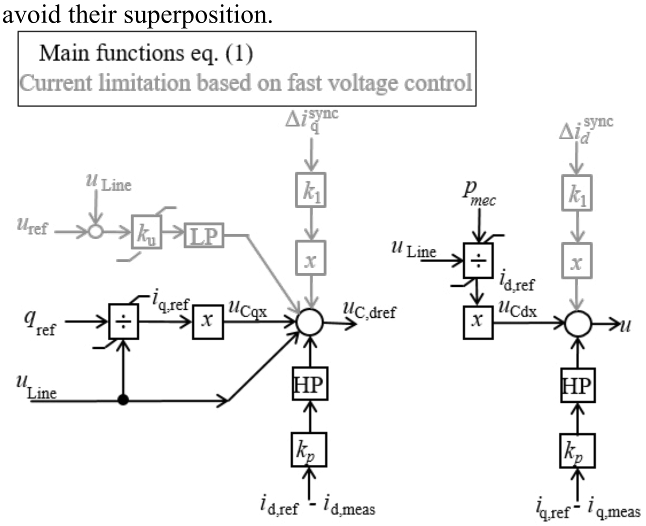

Fig. 2. DVC control diagram

For the current limitation, difference currents $\Delta i_d = i_{d,ref} - i_{d,meas}$ and $\Delta i_q = i_{q,ref} - i_{q,meas}$ are derived from a magnitude limitation, which leaves the angle of the fault current unaffected, turned into difference voltages, and then implemented to eq. (3)-(4). These results are in voltage-based current limitation because the converter output voltage is influenced by this method. This method is only applied to the current components that are above the apparent current limit of 1.1 pu, thus keeping the inverter output voltage at the limit of what is possible for the inverter and not interfering with the control functions of the GFC- DVC itself. Also, no additional controllers or control functions have to be switched on or off. By parameterization of k_1, the intensity of the current limitation intervention can be influenced to improve the dynamic behavior. The output of fast voltage control during fault limitation is 0.16. By selecting $k_1>1$ *e.g.* $k_1 = 1.5$, $k_1 {*} x = 0.24$, the control action of the current limitation is predominant. The control structure, however, is applicable for other priorities for current limitation as well [Denecke et al (2021)].

$$u_{C,d} = u_{Line} - x i_{q,ref} - k_1 x \Delta i_q - k_u (u_{Line} - u_{ref}) - r_{virt} HP(s)(i_{d,ref} - i_{d,meas}) \quad (3)$$

$$u_{C,q} = -x i_{d,ref} - k_1 x \Delta i_d - r_{virt} HP(s)(i_{d,ref} - i_{d,meas}) \quad (4)$$

3. SEPARATED SYNCHRONIZATION AND RoCoF CONTROLLER LOOP FOR DVC

3.1. Synchronization

Orderly operation of electrical grids requires at least a steady-state power flow on the transmission lines. For this purpose, the generating plants in the grid must agree on a common frequency, whose time average value is usually 50 Hz or 60 Hz. However, generation plants must be able to leave this frequency, at least briefly, to adopt a different relative angle with respect to the grid and thus a different feed-in. This means that the generation plants can be operated with power control. A control difference of this power control contributes to the overall active power balance error of the system, based on which all generators leave steady-state operation and accelerate or decelerate due to the integral relationship between power and frequency of the synchronous generators. This can then be observed globally based on the system frequency and a decentralized controller without communication (primary controller) can be used to adjust the generator speeds, which is equivalent to balancing the power of the grid.

The synchronization of the LSC to the grid can be defined as the process of minimizing the difference in the phase, the frequency, and the magnitude between the LSC output voltage and the grid voltage, which is allocated to the grid following the converter. An ideal synchronization technique should promptly respond to any grid changes, well track the phase angle of the grid, adeptly detect any variation in the grid frequency, and effectively isolate the harmonic components and disturbance from the fundamental waveform. GFC controls artificially establish the relationship between power and frequency, which does not exist in voltage source converters for technological reasons. Using the swing equation, the difference between a virtual mechanical power p_{mec} and the actual electrical output power p_e of the inverter determines the change in frequency and angle of the inverter output voltage. This is changed until both input signals are identical. In this way, the power control of conventional power plants is reproduced and, in principle, the same conditions regarding power and frequency control or stabilization apply as for synchronous generators.

3.2. Proposed Synchronization

The synchronization of the converters should ideally take place quickly, but in the first instance robustly. With fast synchronization, the internal phase of the converter control ensures a d/q-frame is always in phase, with the grid voltage so that active and reactive power can be controlled separately without interference with each other. In this study, Firstly for DVC controller, voltage-based synchronization (VBS) contributes to PBS together using k_{lim} factor, to compensate deficiencies for each other (fig. 3). Secondly, according to fig. 3, proposal PBS synchronization consists of two oscillation equations. The first one called fast swing equations ($T_{a,\,fast}$, k_{d1}, k_ω, k_{lim}) - serves mainly the purpose of a strongly damped power-based synchronization and provides only limited virtual inertia. Therefore, virtual inertia is provided by the second weakly damped called slow swing equation ($T_{a,\,slow}$, k_{d2}, k_{In}). This division has the advantage that these control functions, separated in this way, can each be optimized specifically for their purpose, and thus no trade-off has to be made between the individual functions (inertia and frequency control vs. synchronization) in the overall behavior of the synchronization.

Damping and stabilization of the state variable ω_{swing} is usually done in relation to a fixed speed reference ω_{swing}^{ref} =1 pu in swing equations. This automatically leads, to a strong frequency power or primary control behavior, due to the high damping k_{d1} for the synchronization, which is undesirable. To avoid this, we use here a structure according to the top part of fig. 3

under the constraint eq. (6). Here the state variable ω_{swing}^{fast} of the swing equation is stabilized to the grid frequency ω_{PLL} measured using a PLL via the factor k_{d1}. Thus, the fast oscillation equation has no frequency power or primary control behavior and can inject any desired active power at any prevailing frequency. Nevertheless, the possibility remains open to generating a primary control behavior using the factor k_ω, which is then independent of the high damping of the synchronization. Thus, the user has the choice to participate in frequency control. The control loop with $\Delta\omega_{swing}^{fast}$ (fig. 3) is not completely replaced by the control loop with $\Delta\omega_{PLL}$. It is replaced with a relatively small factor according to eq. (5), since the damping of the system itself as well as the connected grids can be significantly improved at sub-synchronous frequencies, primary control can be achieved in the order of conventional power plants' scale and island grid capabilities.

$$(d\omega_{swing}^{fast})/dt = T_{a,fast}[p_{mec} - p_e + k_{d2}(\omega_{swing}^{fast} - \omega^{Grid}) + k_\omega(\omega_{swing}^{fast} - \omega^{ref})] \quad (5)$$

$$k_\omega \ll k_{d1} \quad (6)$$

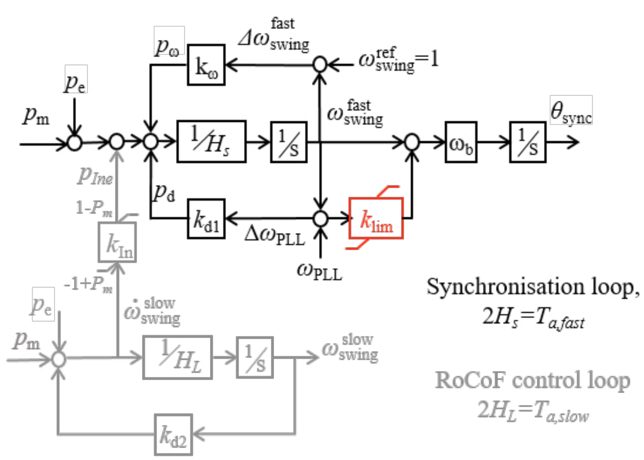

Fig. 3. Separated synchronization and RoCoF control loop

Aforesaid, the quick, instantaneous, and robust estimated phase angle and frequency of VBS, ω_{PLL} under unbalanced and distorted grid conditions, come up with slow inertial nature of PBS (in comparison to VBS not second slow swing equation) ω_{swing}^{fast}, stabilizes and controls the grid externally and internally which is represented as ω_{sync} and shows in:

$$\omega_{sync} = \omega_{swing}^{fast} + k_{\lim}(\omega_{PLL} - \omega_{swing}^{fast}) \quad (7)$$

The k_{lim} factor defines the rate of VBS contribution with PBS in case of synchronization and is also considered as a part of the current control limitation. For modeling, the fully DVC in a d/q frame, the phase angle θ_{sync} which is derived from introduced eq. (7) in grid-connected mode must be constant under steady-state conditions. It has to correspond to the phase displacement between the virtual position of the GFC internal voltage and the position of the grid voltage vector, which is defined by:

$$d\theta_{sync}/dt = \omega_{sync} \quad (8)$$

3.3. Virtual Inertia, RoCoF control loop

The inertia effect, which is supposed to relieve the synchronous generators from mechanical stress and thus also smooth the mains frequency, can in principle be performed as a kind of RoCoF control by injecting power p_{In} proportional to the measured RoCoF. However, since in general gradients are difficult to measure and thus only few possibilities are available in the controller design except for setting the proportional gain k_{In} - in this work, we generate an artificial Rocof signal using the second slow oscillation equation (fig. 3 H_L, k_{d2}, k_{In}), which is more weakly damped contrary to the fast oscillation equation. Moreover, this gives the possibility to adjust it e.g. empirically, by pole placement, or using an optimal or robust optimization criterion. This weak damping is enabled by synchronization using the fast oscillation equation, allowing inertia to be provided over longer periods of time $T_{a,slow}$ and thus supporting the power system frequency more effectively. This second oscillation equation is coupled to the first one (fig. 3 H_S, kd_1, $k\omega$, k_{lim}) by supplying this artificial Rocof signal like another dispatch to the first one, via proportional gain k_{In}. Since both oscillation equations are decoupled, the parameters can be freely adjusted in wide parameter ranges, but stability must be taken into account.

4. PERFORMANCE ILLUSTRATION IN TEST SYSTEM

A 400/220 kV 16-machine dynamic test system known as PST16 has been developed based on characteristic parameters of the European power system. The network consists of 3 strongly meshed areas, which are connected by long-distance transmission lines [S.P. Teeuwsen et al (2003)]. In this paper, the meshed area B of the network is considered to study the frequency dynamics, which is shown in Fig. 4. The system is modified by adding wind turbines, which are equipped with fully GFC- DVC and proposed separated synchronization-RoCoF control loops.

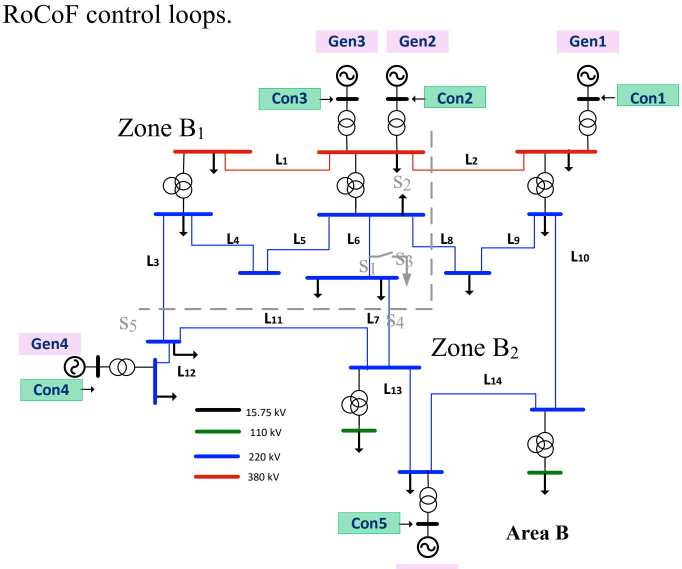

Fig. 4. Layout of test system

4.1. Separated primary and RoCoF controller Functionality

The purpose of this section is to prove the functionality of the (synchronization and RoCoF control loops for DVC) Synch-RoCoF- DVC in case of the primary control response, RoCoF, and nadir of the test system. For this purpose, first, the frequency of the test system is investigated and compared in different combinations of GFC based on DVC and SG while after 20 seconds, the switch S_1 adds 250MW additional load. A distinction is made between 5 scenarios (tab. 1).

Table 1. Synchronization (Primary) and inertia scenarios

Scenario	Description
A	Only synchronous Generator (SG) in the grid
B	Converter (Con) 1, 4, 5 with Synch-DVC, $T_{a,fast}$=0.125s & SG 2, 3
C	Con 1, 4, 5 with Synch-RoCoF-DVC, $T_{a,fast}$=0.125s, $T_{a,slow}$=1.25s & SG 2, 3
D	Con 1, 4, 5 with Synch-RoCoF-DVC, $T_{a,fast}$=0.125s, $T_{a,slow}$=2.5s & SG 2, 3
E	Con 1, 4, 5 with Synch-RoCoF-DVC, $T_{a,fast}$=0.125s, $T_{a,slow}$=5s & SG 2, 3

The synchronous generators are equipped with a primary controller with a droop factor of 5%. To create the same conditions, the factor k_ω is set in the converters to k_ω= 20. Three aggregated 1550-, 2×1000-MVA, Con1, 4, and 5 controlled using DVC with the contribution of 2×1300-MVA-Gen 2, 3 are considered for scenarios B-E.

Fig. 5 shows the results of a frequency measurement on line L_8 for scenarios A-E (tab. 1). The diagram on the left shows frequency dynamics for all scenarios in detail. The small differences in the steady frequency between the scenarios with only synchronous generators (A) and the scenarios with converters (B-E) are due to the different network PCCs of the converters, which are associated with somewhat greater losses.

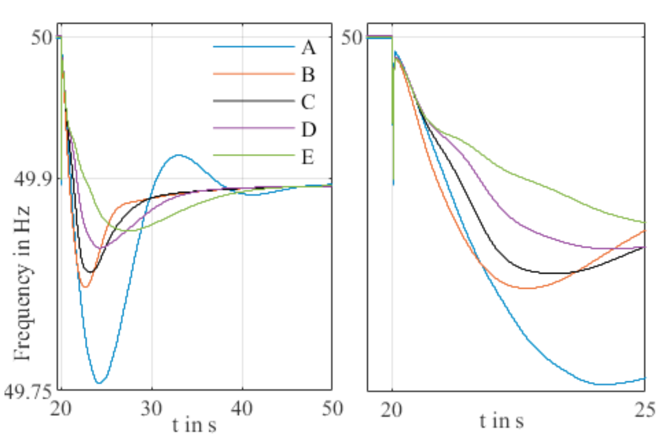

Fig. 5. Frequency response of 5 mentioned scenarios

In scenarios B-E, where converters Con 1, 4, 5 are replacing Gen 1, 4, and 5 in the grid, you can see a significantly higher nadir compared to scenario A, which is due to the instantaneous primary control via the factor k_ω. Since Con 1, 4, and 5 make up more than 60% of the generation in the test system in scenarios B-E; they can make a major contribution to the primary control, but can otherwise also follow the grid frequency via the factor k_{d1}. A comparison between scenarios A and B shows that a direct inclusion of inertia in the synchronization swing equation causes only little improvement in RoCoF, which is due to the high damping k_{d1} required for synchronization. In the second swing equation for the formation of the RoCof signal (fig. 5), the damping k_{d2} can be selected to be very low, so that the inertial response of this does not decay over a long period of time and thus results in more significant improvements of RoCoF and nadir in scenario C-E. The second swing equation can be set independently and represents a deterministic possibility of providing inertia since no noisy frequency gradients have to be measured here.

4.2 System split, islanding operation, and resynchronization

The system splitting can lead to power system breakdown and lead to an over/under frequency, voltage, and actual risk of system collapse. This depends upon the point of separation and the number of loads and generation units in a given area. The increase of transmission capacities and renewable generation share lead to high power imbalance and interfaced power electronics generators do not provide an inherent contribution to the frequency dynamics and can be subjected to disconnections.

For the simulation and analysis of the system split, islanding, and resynchronization scenarios with a high share of renewable energy, like the last part combination of Con1, 4, 5 with Synch- RoCoF- DVC (around 60% converter based generator) with Gen 2, 3 is considered. The grid has been split through L_2, L_3, L_7 and L_8 via switches S_2, S_3, S_4 and S_5 switches at t_{split}=40 s As a result the grid is divided into 2 separated zones, zone B_1 with 100% converter based generator and zone B_2 with 100% conventional synchronous generator. These 2 islanded grids continue working stable in island mode for more than 38 seconds and at $t_{resynch}$=78 s would be connected through the same lines and switches. Fig. 6 shows the results of a frequency response of Con 1, 4, 5, and Gen 2, 3 for system split, islanding, and resynchronization scenarios.

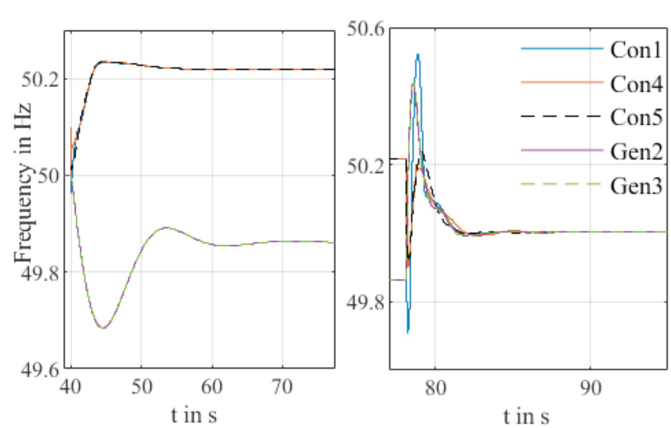

Fig.6. Frequency response of system split & resynchronization

The diagram on the left indicates the frequency response (inertial and primary behavior) at splitting time t_{split}= 40 s as well as islanding mode in the next 38 sec, grid splitting causes over-frequency in the converter-based zone and under-frequency in the conventional generator's zone. Frequency stability is shown in both zones so even in zone B_2 (fig 6) with 100% converter based is managed by DVC and its new separated Synch-RoCoF-DVC control. The diagram on the right side shows the frequency response at re-synchronous time $t_{resynch}$= 78 s and post post-transient behavior. As you can see, the frequency returns to nominal value of 50 Hz after the resynchronization of split grids.

5. CONCLUSIONS

This paper improved the synchronization control loop of decoupled GFC- DVC in d/q reference frame. The proposed controller considers separated control loops for fast synchronization with small inertia and slow inertia response to take advantage of the fast response of the converter, and time frames of inertial response and primary frequency control for an effective control capability for the converter for both timeframes after a disturbance. The proposed separated controller determines desirable independent parametrization for inertia from other control characteristics. The functionality the of proposed controller was examined, ,compared and proved with frequency response and its features like nadir and RoCoF with additional load as well as system split, islanding and re-synchronization scenarios. For simplification, the converters have been designed as average models and provided with identical parameters for all converters in the grid, to exclude the over-fitting of the parameters for the specific application site and to prove the robustness of the DVC. The following work on the GFC- DVC will address, optimal and robust RoCoF control, detailed voltage reactive power control in the outer control loop of DVC, and interaction of converters equipped with DVC on each other as well as present a GFC- STATCOM variant of the DVC.

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