A Current Controlled Virtual Synchronous Machine Adapted for Operation under Unbalanced Conditions

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Abstract—This paper presents a comprehensive evaluation of control strategies for operation of a Virtual Synchronous Machine (VSM) under unbalanced conditions in both grid-connected and islanded mode. The basis for the evaluation is a Current Controlled VSM where a quasi-stationary virtual impedance emulates a simplified positive sequence electrical model of a synchronous machine. It is shown how three general strategies can be selected for controlling the negative sequence currents: 1) calculation of the negative sequence current references according to the desired active and reactive power flow characteristics, 2) applying a negative sequence virtual impedance resulting in unbalanced currents as in the steady-state response of a synchronous machine, or 3) operation with a negative sequence voltage controller for eliminating unbalances in the locally measured voltages. For the first approach, three objectives for shaping the power flow characteristics can be selected: I) balanced three-phase currents, II) constant instantaneous active power flow, or III) constant instantaneous reactive power flow. Comprehensive simulation results are presented to evaluate the performance and applicability under grid connected and islanded operation. The results demonstrate how utilization of the negative sequence currents to control the power flow characteristics is only applicable for grid connected operation, while the other two approaches can be utilized in both islanded and grid-connected modes. However, closed loop control for balancing the local voltages depends on a high equivalent grid impedance and is not suitable for operation in strong grid conditions.

Keywords— Grid connected VSCs, Islanded Power Systems, Unbalanced Grids, Virtual Synchronous Machines

I. INTRODUCTION

The control of power electronic converters as Virtual Synchronous Machines (VSMs) has been extensively studied during the last decade [1]-[3]. Indeed, many control schemes for emulating the behaviour of Synchronous Machines (SMs) with power converters have been proposed, including concepts labelled as Virtual Synchronous Generators (VSGs) Synchronverters, or Synchronous Power Controllers (SPCs)[3]-[7]. A first motivation for pursuing such control strategies has been to provide virtual inertia in modern power systems with declining equivalent rotating inertia due to the increased share of generation with power electronic interfaces. Furthermore, control strategies relying on a similar power-balance-based synchronization mechanism as SMs enable operation in grid-connected as well as in

islanded mode. Thus, a second motivation for pursuing VSM-based control strategies is to ensure grid forming capability, which is attractive for applications where both grid-connected and stand-alone operation are required.

In the literature, three general control approaches have been applied for actuating the reference voltage amplitude and the phase angle resulting from the inertia model of a VSM [3]: i) In the simplest strategies, these reference values are directly applied to the modulation stage of the converter [3]-[6]. This approach can be referred to as VSMs with Directly Applied Voltage (DAV); ii) alternatively, a closed loop voltage control cascaded with an inner current control loop can be implemented [3], [8]. This control structure can be referred to as a Voltage Controlled (VC) VSM. For both these types of control, a virtual impedance can be utilized to emulate the stator impedance of an SM. iii) The third common approach for VSM-based control is to utilize a virtual impedance, or a virtual admittance, to translate the voltage reference from the SM model into current references for a conventional current control loop [3], [7], [9]. This approach can be generally referred to as a Current Controlled (CC) VSM.

The majority of the VSM-based control implementations proposed in literature are not directly applicable under unbalanced conditions. Thus, further enhancements are needed for controlling the response to the negative sequence component of the voltages. Recent publications have addressed this issue by proposing different ways of controlling the negative sequence currents during operation in unbalanced grids [10]-[15]. Although configurations including direct or closed loop voltage control have been applied for unbalanced conditions in [10], [11], the requirements for limiting the currents under unbalanced grid faults generally favours current controlled implementations. Thus, it is shown in [12]-[16] how CCVSM-based strategies can be combined with different objectives for calculating negative sequence current references. Specifically, it is shown how the negative sequence currents can be calculated by imposing either I) balanced three phase currents, II) elimination of active power oscillations or III) elimination of reactive power oscillations. However, these studies consider only the operation under unbalanced conditions in grid-connected mode when the negative sequence currents can be controlled without significantly influencing the voltage. On the other hand, [17] discusses a VSM-based control for an islanded system where a CCVSM-based strategy controlling the positive sequence currents is combined with a negative sequence voltage controller for eliminating unbalances in the local voltage. Similarly, the VCVSM based control in [11] includes an option for directly generating balanced voltages
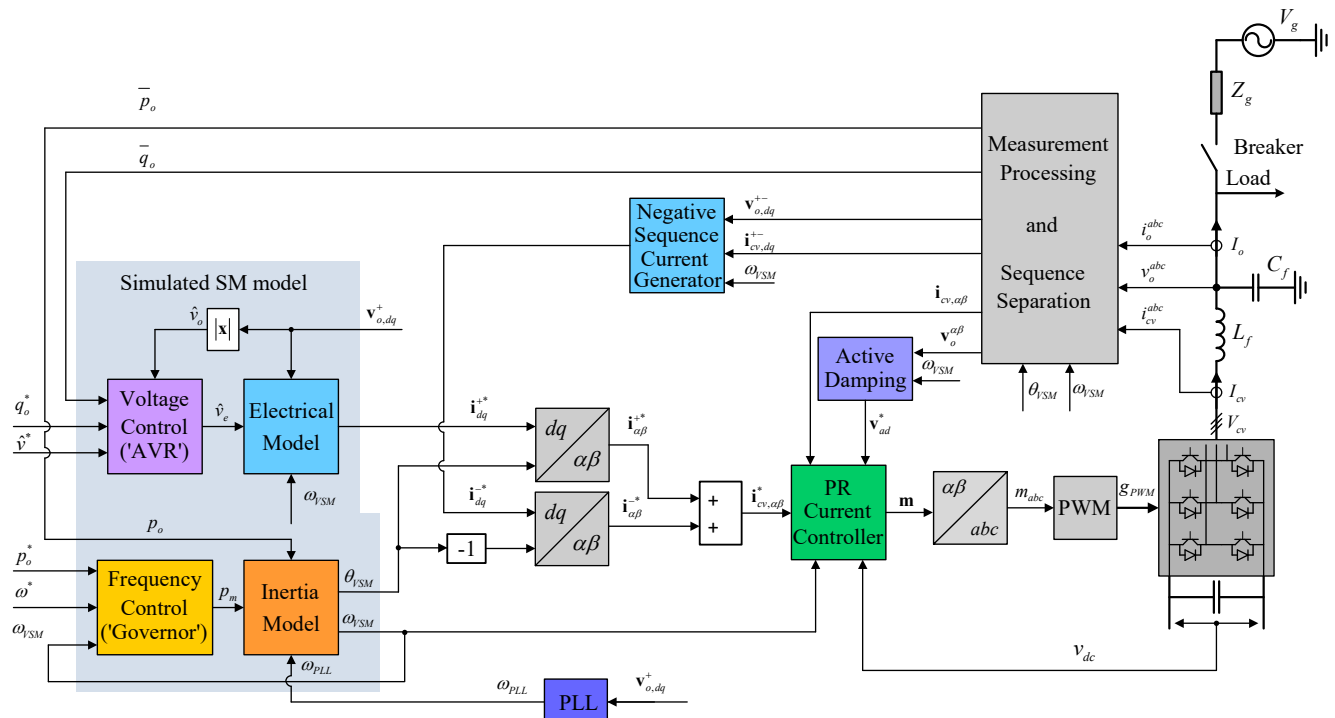
Fig. 1 Overview of the CCVSM-based control strategy for unbalanced grid-connected and islanded operation

when operating in islanded mode. However, none of these publications have comprehensively studied the alternative control options under unbalanced conditions for both grid-connected and islanded operation.

This paper presents a thorough evaluation of operating strategies for a CCVSM under unbalanced conditions in both grid-connected and islanded modes. It is first shown how three general strategies can be utilized for controlling the negative sequence currents: 1) calculation of the negative sequence current references according to the desired active and reactive power flow characteristics, 2) introduction of a negative sequence virtual impedance, and 3) operation with a negative sequence voltage controller. For all cases, only the dc-components of the power flow are used as feedback signals for the active and reactive power control, ensuring that the outer control loops are not influenced by double frequency power oscillations. A comprehensive set of simulation results illustrates the performance of the presented options for controlling the negative sequence currents under unbalanced conditions in grid-connected and islanded modes, as well as for the transition from grid-connected to islanded operation. The results demonstrate how the strategies for controlling the power flow characteristics are only suitable for grid-connected operation. Furthermore, the results indicate how operation with negative sequence voltage control is only applicable in islanded operation or in conditions with a relatively high equivalent grid impedance. The results offer an overview of the general control objectives that can be applied for VSM-based control under unbalanced conditions and can serve as a basis for defining suitable strategies for transitioning between grid-connected and islanded operation.

II. VSM-BASED CONTROL UNDER UNBALANCED CONDITIONS

The system configuration shown in Fig. 1 is utilized to evaluate the different options for operation during unbalanced conditions. In this structure, a Voltage Source Converter (VSC) operated as a CCVSM is connected to a local power system through an LC filter. The configuration includes a local passive load connected close to the converter and can be separated from the main grid by a breaker. In the figure, upper case symbols indicate physical variables or parameters, while lower case symbols indicate per unit quantities used in the control system. The main measurements utilized by the VSM-based control are the three phase values of the converter currents i_{cv}, the filter output voltages v_o, and the output current i_o.

A. Overview of CCVMS control structure

The general structure of the CCVSM implementation shown in Fig. 1 is adapted from the control system presented in [9]. However, Proportional-Resonant (PR) controllers are utilized for the inner loop current regulation to simplify the implementation while ensuring the capability to control positive and negative sequence currents. These controllers operate directly on the converter currents $\mathbf{i}_{cv}$ in the stationary $\alpha\beta$ reference frame. Furthermore, active damping of LC filter oscillations is introduced by using a band-pass filter based on a Second Order Generalized Integrator (SOGI) configured as a Quadrature Signal Generator (QSG) [18]. The structure of the active damping can be considered as a stationary frame equivalent to the dq-frame active damping used in [9] Thus, the frequency characteristics of the damping can be adjusted by tuning the internal gain of the SOGI-QSG.

B. Sequence separation and power calculation for VSM operation under unbalanced conditions

Access to the positive and negative sequence components of the voltages and currents is needed to control the converter operation under unbalanced conditions. This is achieved by a dual set of SOGI-QSGs (i.e. a DSOGI-QSG) according to [18]. Using the voltage as an example, a block diagram showing how the DSOGI-QSGs structure generates the in-phase and in-quadrature components required for Positive and Negative Sequence Calculation (PNSC) is shown in Fig. 2. The only difference from the
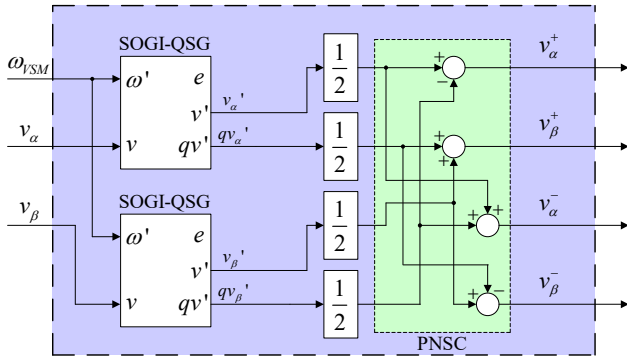
Fig. 2 Sequence separation of voltage measurements by DSOGI-QSG with frequency adaptivity provided by the VSM speed

Fig. 3 Inertia model implemented by a virtual swing equation operated with an ideal frequency droop as a 'governor' function

implementation in [18] is that frequency adaptivity of the DSOGI-QSG is ensured by using the VSM speed instead of a frequency estimation based on the voltage measurements.

By estimating the positive and negative sequence components of the measured voltages and currents, the average values or dc-components of the active and reactive power flow can be directly calculated as:

$$\bar{p}_o = v_{o,\alpha}^+ \cdot i_{o,\alpha}^+ + v_{o,\beta}^+ \cdot i_{o,\beta}^+ + v_{o,\alpha}^- \cdot i_{o,\alpha}^- + v_{o,\beta}^- \cdot i_{o,\beta}^-$$
$$\bar{q}_o = -v_{o,\alpha}^+ \cdot i_{o,\beta}^+ + v_{o,\beta}^+ \cdot i_{o,\alpha}^+ - v_{o,\alpha}^- \cdot i_{o,\beta}^- + v_{o,\beta}^- \cdot i_{o,\alpha}^-$$

(1)

The resulting values of average active and reactive powers are used directly as the feedback signals indicated in Fig. 1.

C. Virtual Swing equation and electrical model of CCVSM

The structure of the virtual swing equation used for inertia emulation and power-balance-based synchronization in the CCVSM is the same as presented in [8], [20]. A block diagram of the implemented Inertia Model, given by a virtual swing equation, and the frequency droop (i.e. 'governor' function in Fig. 1) acting on the input power to the swing equation, is shown in Fig. 3. Thus, the VSM swing equation can be expressed as:

$$T_a \frac{d\omega_{VSM}}{dt} = p^* + k_\omega \left(\omega_{VSM}^* - \omega_{VSM} \right) - \bar{p}_o + k_d \left(\omega_{VSM} - \omega_{PLL} \right)$$ (2)

Here, p_o^* is the external power reference set-point and $\bar{p}_o$ is the average power flowing from the VSC into the grid as given by (1). Furthermore, k_ω is the droop gain acting on the difference between the frequency reference, ω_{VSM}^*, and the emulated speed ω_{VSM}, while k_d is the damping coefficient. The inertial damping is implemented by multiplying k_d with the difference between ω_{VSM} and a frequency estimate ω_{PLL} provided by a Phase Locked Loop (PLL). It should be noted that the PLL is operating on the positive sequence voltage component and is only used for estimating the frequency since the grid synchronization is provided by the virtual swing equation. Indeed, the emulated speed is defined by the integral of the power balance, and the phase angle of the positive sequence rotating reference frame is given by the integral of the VSM speed. The only difference between (2) and the dynamic equation for the VSM speed in [8], [20] is that $\bar{p}_o$ from (1) is used instead of the instantaneous three phase power flow. Thus, any double frequency power oscillations resulting from unbalanced conditions will not influence the inertial dynamics of the VSM.

The Quasi-Stationary Electrical Model (QSEM) from [9] is used for emulating an SM stator impedance for the positive sequence control. Thus, the positive sequence current reference vector is calculated as:
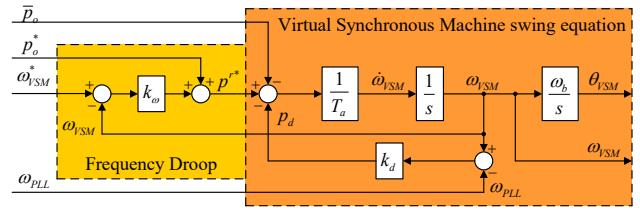
$$\mathbf{i}_o^+ = \frac{\hat{v}_e - \mathbf{v}_o^+}{r_v^+ + j\omega_{VSM} l_v^+}$$ (3)

In this equation, $\hat{v}_e$ is the internal positive sequence voltage amplitude of the VSM, and r_v^+, l_v^+ are the corresponding per unit virtual resistance and inductance. The positive sequence voltage component $\mathbf{v}_o^+$ is obtained from the DSOGI-QSG as shown in Fig. 2. Due to the filtering effect of the DSOGI-QSG, there is no need for additional filtering of the voltages as discussed in [18].

Finally, the amplitude of the internal positive sequence VSM voltage in (3) is calculated by a reactive power droop,

$$\hat{v}_e = \hat{v}_e^* + k_q \left(q^* - \bar{q}_o \right),$$ (4)

where $\hat{v}_e^*$ is the internal reference for the positive sequence voltage amplitude. Furthermore, q^* is the reactive power reference, $\bar{q}_o$ is the average measured reactive power and k_q is the reactive power droop gain. In order to limit the reactive power flow during voltage sags, $\hat{v}_e$ is also limited to be within ± 0.05 pu of the actual measured positive sequence voltage, such that $0.95|\mathbf{v}_o^+| < \hat{v}_e < 1.05|\mathbf{v}_o^+|$.

D. Control of the negative sequence currents

The power flow characteristics of the VSM and the impact on the local voltages during unbalanced conditions will be determined by the control of the negative sequence currents. In general, three different approaches can be pursued for controlling the negative sequence current: 1) calculation of the negative sequence current references for shaping the active and reactive power flow characteristics, 2) applying a negative sequence virtual impedance resulting in unbalanced currents equivalently to the steady-state response of a synchronous machine, or 3) operation with a negative sequence voltage controller for eliminating unbalances in the locally measured voltages. These three approaches are explained in the following.

1) Calculation of negative sequence current references for shaping the power flow characteristics.

As discussed in [13], [14], the negative sequence current references can be calculated according to the desired power flow characteristics. This control approach is equivalent to corresponding conventional PLL-based strategies for active and reactive power flow control under unbalanced conditions [19]. Thus, three different objectives can be defined for controlling the negative sequence currents as I) obtaining balanced three-phase currents, II) eliminating oscillations in the active power flow, or III) eliminating oscillations in the reactive power flow.

The simplest control approach is to set the negative sequence current references to zero, which directly ensures balanced three phase currents. This strategy is referred to as Balanced Positive Sequence Current (BPSC).

If the objective is to eliminate the active power oscillations, the negative sequence current references can be calculated as a function of the voltage components and the positive sequence currents resulting from (3). As derived in [13], the negative sequence current references required for controlling constant active power (CAP) can be expressed as:

$$\mathbf{i}_o^{-*}{}_{CAP} = \begin{bmatrix} i_d^{-*} \\ i_q^{-*} \end{bmatrix}_{CAP} = \frac{-1}{(v_{o,d}^+)^2 + (v_{o,q}^+)^2} \cdot$$
$$\begin{bmatrix} v_{o,d}^+ v_{o,d}^- - v_{o,q}^+ v_{o,q}^- & v_{o,q}^+ v_{o,d}^- + v_{o,d}^+ v_{o,q}^- \\ v_{o,q}^+ v_{o,d}^- + v_{o,d}^+ v_{o,q}^- & v_{o,q}^+ v_{o,q}^- - v_{o,d}^+ v_{o,d}^- \end{bmatrix} \begin{bmatrix} i_{o,d}^+ \\ i_{o,q}^+ \end{bmatrix} \quad (5)$$

A similar equation can be derived for ensuring constant reactive power (CRP) during unbalanced conditions [13]. The resulting current references can be expressed as:

$$\mathbf{i}^{-*}{}_{CRP} = -\mathbf{i}^{-*}{}_{CAP} \quad (6)$$

The negative sequence current references for the three defined cases can be easily generalized into a single control scheme as discussed in [13]. In the following, the case of balanced three phase currents is considered separately, while the cases of CAP or CRP are integrated into a single function, as shown in the upper part of Fig. 4.

Although these three strategies can be suitable for VSMs in grid-connected mode, they are mostly relevant for operation under strong grid conditions when the output currents of the VSM will not significantly influence the local voltage. Furthermore, these strategies are not necessarily directly applicable or suitable for operation in weak grids or in islanded mode with unbalanced loads.

2) Operation with negative sequence virtual impedance

The negative sequence currents can be defined by a negative sequence impedance in the same way as the positive sequence current references. Applying the same quasi-stationary equations for representing the negative sequence virtual impedance, the negative sequence current references can be expressed as:

$$i_d^{-*} = \frac{\left(v_d^{-*} - v_d^-\right) r_v^- - \left(v_q^{-*} - v_q^-\right) \omega_{VSM} l_v^-}{\left(r_v^-\right)^2 + \left(\omega_{VSM} l_v^-\right)^2},$$
$$i_q^{-*} = \frac{\left(v_q^{-*} - v_q^-\right) r_v^- + \left(v_d^{-*} - v_d^-\right) \omega_{VSM} l_v^-}{\left(r_v^-\right)^2 + \left(\omega_{VSM} l_v^-\right)^2} \quad (7)$$

Setting the negative sequence voltage references v_d^{-*} and v_q^{-*} to zero as shown in the middle of Fig. 4, results in a negative sequence current depending on the equivalent impedance, like in a regular synchronous machine. Indeed, the virtual resistance and inductance r_v^- and l_v^- for the negative sequence can be specified to different values than for the positive sequence. However, this strategy would imply unbalanced currents in response to unbalanced voltages, depending on the virtual impedance and the equivalent grid impedance.

3) Operation with negative sequence voltage control

In case of operation in weak or islanded grids, the VSM could be capable of balancing the local voltages. Especially in islanded conditions, it could be required from the VSM to provide balanced voltages independently of any unbalances in the local load. Since the local load and/or grid impedance can change significantly, such local voltage balancing should be obtained by closed loop control. This can be implemented
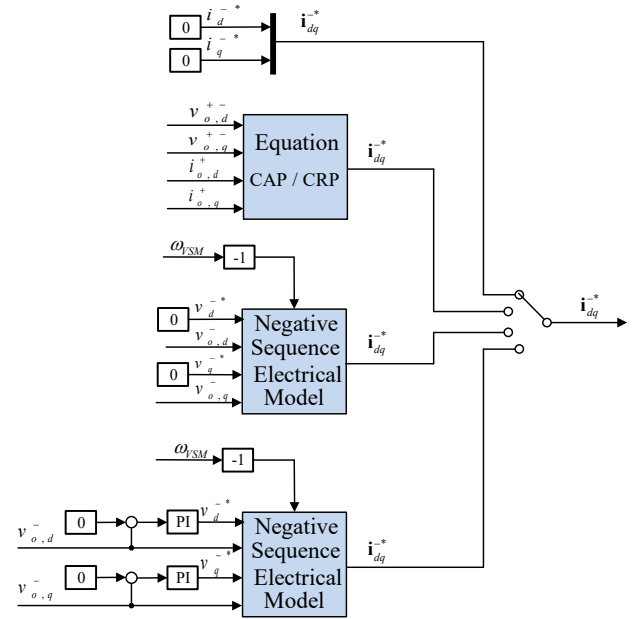

Fig. 4 Flexible selection of control objectives for the negative sequence current references

TABLE I
PARAMETERS OF THE INVESTIGATED SYSTEM CONFIGURATION

Parameter	Value	Parameter	Value
AC Voltage $V_{ll,g,n}$	400 V	Rated current	72 A
Rated angular frequency ω_n	2π·50 Hz	Primary filter inductance l_f, r_{lf}	0.08pu, 0.008pu
DC voltage V_{dcn}	686 V	Filter capacitance c_f	0.079 pu
Active damping k_{SOGI}, k_{AD}	√2 0.5 pu	Grid-side filter inductance l_g, r_g	0.2pu, 0.01pu
Current controller gains, kpc,kic	1.2 0.8	DSOGI-QSGs for sequence separation k_{SOGI}	√2
VSM Positive Seq. Impedance, r_v^+, l_v^+	0.01 pu 0.2 pu	PLL PI controller, $k_{p,PLL}$, $k_{i,PLL}$	2, 70
VSM Negative Seq. Impedance, r_v^-, l_v^-	0.01 pu 0.2 pu	Negative sequence voltage control, $k_{p,NS}$, $k_{i,NS}$	0.1, 5
Virtual inertia Ta	10 s	VSM damping k_d	200 pu
Frequency droop k_ω	20 pu	Reactive power droop k_q	0 pu

in several different ways, for instance by a controller directly providing the negative sequence voltage components as proposed in [17]. In this paper, an approach relying on the virtual impedance is preferred, to ensure that the current references can be easily limited in case of severe unbalanced conditions. Thus, two PI controllers are applied for providing the internal negative sequence voltage references to be applied in (7). The resulting control structure is also illustrated in the lower part of Fig. 4.

III. SIMULATION RESULTS

Time domain simulations in the Matlab/Simulink/ SimPowerSystems environment have been conducted to evaluate the performance and applicability of all the presented control strategies. A comprehensive set of results is presented in the following, to illustrate the operation in both grid-connected and islanded modes.

A. Case description

The simulations are based on the system configuration from Fig. 1 with parameters given in Table I. The performance of the investigated strategies is first studied in response to an unbalanced voltage sag. The inertial response is also verified for power and frequency transients under unbalanced grid voltages. Then, the transient resulting from
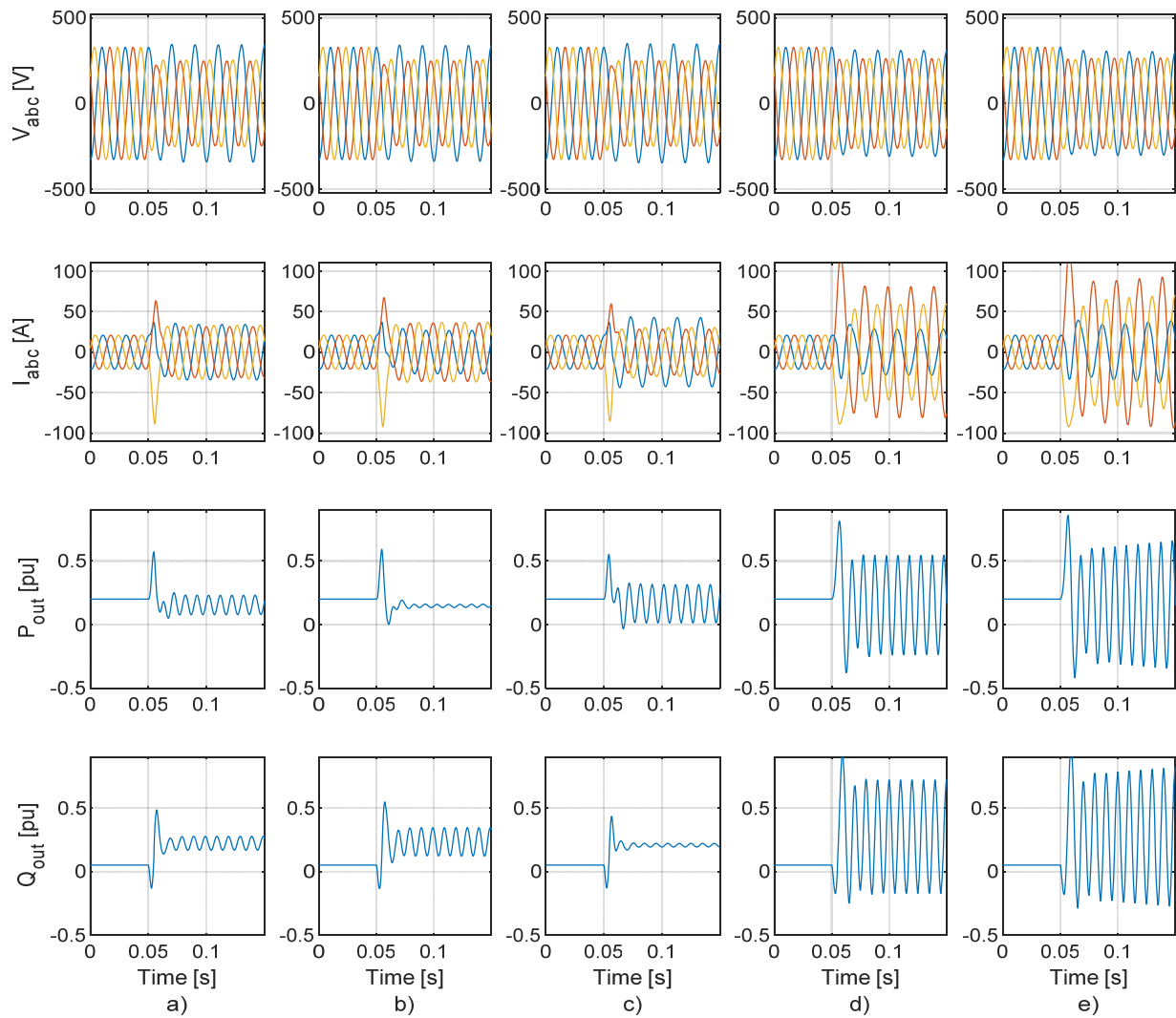
Fig. 5 Simulation results in grid-connected mode showing the transient response to an unbalanced voltage sag occurring at t=0.05, resulting in a grid voltage with 25% unbalance ($|V^-|/|V^+| = 0.2/0.8=0.25$). a) Balanced positive sequence currents b) Constant active power c) Constant reactive power, d) Negative sequence virtual impedance e) Negative sequence voltage controller.

islanding of a small system that includes only the VSM and a local unbalanced resistive load is simulated. These results serve to illustrate which solutions can be suitable for islanded operation. The inertial response to changes in the load under unbalanced islanded operation is also evaluated.

B. Unbalanced operation in grid-connected mode

As a first test, the CCVSM is exposed to an unbalanced voltage sag. The response in terms of currents and voltages as well as instantaneous powers is shown in Fig. 5, while a comparison of the average active power flow and the resulting virtual speed of the VSM is shown in Fig. 6. As shown in Fig. 5, an unbalanced voltage sag results in a transient drop of the active power and a significant change of reactive power due to the reduced amplitude of the positive sequence voltage. The positive sequence voltage reference for the VSM is limited to a value close to 0.85 pu, as explained in section II.C to avoid excessive reactive power flow. The results in Fig. 5 a), b) and c) also clearly show how the three cases with BPSC, CAP and CRP respond as expected. The case with a negative sequence virtual impedance results in higher and more unbalanced currents than the three first cases, and correspondingly higher oscillations in the active and reactive power flow. However, the unbalanced currents flowing through the grid-impedance
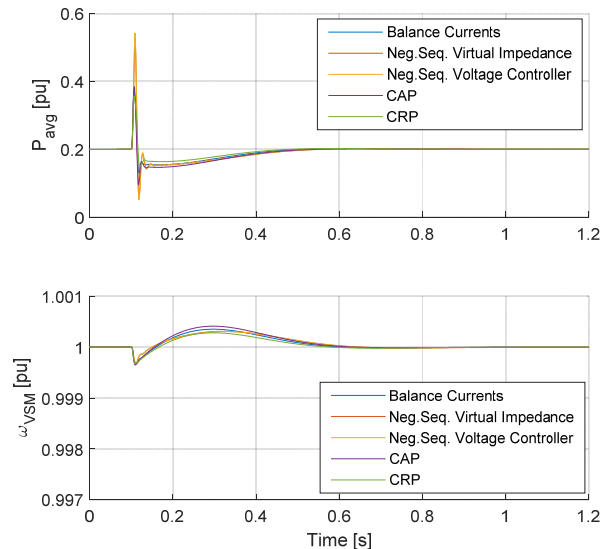

Fig. 6 Comparison of inertial response to an unbalanced voltage sag

is in this case helping to reduce the local unbalance in the voltage. When introducing the closed loop control for eliminating the voltage unbalance, the unbalance of the three phase currents is further increased as shown in Fig. 5 e). A relatively slow response of the balancing controller can also
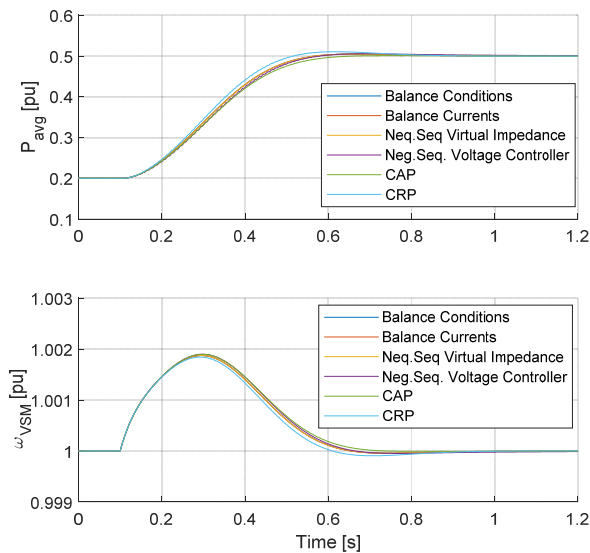
Fig. 7 Comparison of response to a step increase of 0.3 pu in the power reference at t= 0.1 s under unbalanced voltage conditions
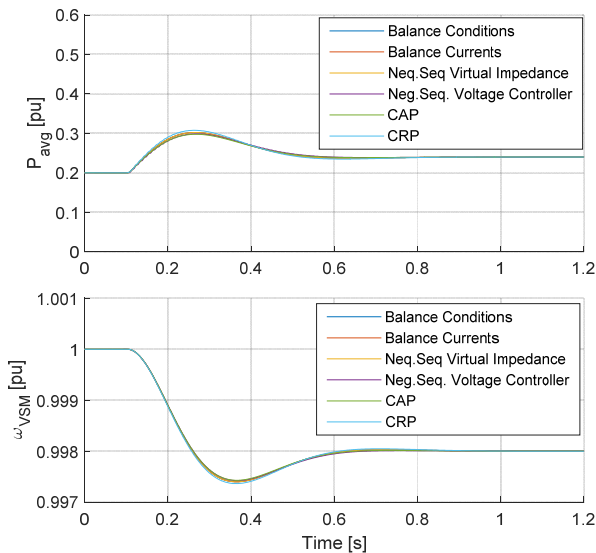

Fig. 8 Comparison of response to a step of −0.1 Hz (=0.002 pu) in the grid frequency at t = 0.1 s under unbalanced voltage conditions

be seen in the figure. The local voltage unbalance is finally eliminated by injecting negative sequence currents into the grid impedance but the maximum current amplitude among the phases depends on the voltage unbalance and the equivalent grid impedance. Therefore, this approach would not be generally applicable in strong grids with a low equivalent grid impedance.

As shown in Fig. 6 there are small differences in the initial transient of the average active power flow between the simulated cases, resulting from the different negative sequence currents, and this has a small influence on the VSM speed. After a transient determined by the inertia model, the power is controlled back to the reference value, and ω_{VSM} returns to the grid frequency of 1.0 pu for all the cases.

To further evaluate the transient response of the evaluated control strategies, the CCVSM is exposed to a step in the active power reference of 0.3 pu and a step in the grid frequency of −0.002 pu, as shown in Fig. 7 and Fig. 8, respectively. As a point of reference, these figures also include a case with balanced grid voltages. The results show some minor differences in the average power during the

transients, which results in corresponding differences in the VSM speed. However, these differences are very small, demonstrating that the influence from the negative sequence current control on the inertial dynamics of the VSM swing equation is limited when operating in grid-connected mode.

C. Transient response to islanding with local load

The studied control strategies are exposed to an islanding transient by switching the breaker indicated in Fig. 1 from closed to open position. After disconnection from the grid, the converter is left to operate in islanded mode with an unbalanced local load with a total power demand of 0.5 pu at rated voltage. The unbalance is created by adding another load between phase *a* and *b* with half the impedance of the initial delta-connected load resistances. The response to the transient is shown in Fig. 9 for all the simulated cases. As clearly shown by the results in Fig. 9 a), b) and c), the cases where the negative sequence current references are directly specified to shape the power flow characteristics are not suitable for islanded operation. Indeed, all these three strategies are generating over-voltages in the phase with the lowest load. The case with balanced three phase currents is also increasing the amplitude of the local negative sequence voltage to 0.4 pu, while the case with constant active power is maintaining a negative sequence voltage in the range of 0.2 pu. The case with CRP is even resulting in an uncontrolled increase in the negative sequence voltage, and a significant increase in the total average load power due to the increased voltage, but without being able to eliminate the reactive power oscillations. Thus, even if operation with BPSC, CAP and CRP can be suitable for operation in strong grids, these control functions should be immediately disabled when transitioning into islanded mode.

The response to the islanding transient for the case with virtual impedance defining the negative sequence currents is shown in Fig. 9 d). In this case, the transient response to the islanding is smooth and fast, with the resulting negative sequence currents contributing to balancing of the load voltage. The resulting amplitude of the negative sequence voltage is then reduced to 0.04 pu. However, since the negative sequence currents are resulting from the virtual impedance, they cannot fully compensate the unbalance caused by the load. Finally, Fig. 9 e) shows the results with the closed loop control for eliminating the voltage unbalance. As expected, this strategy is able to maintain balanced three phase voltages independently of the unbalance in the load resistance. Indeed, the negative sequence currents resulting from this control strategy in steady-state operation correspond to the currents that would result from feeding the load with a balanced three phase voltage source. It is also noted that both these strategies provide unbalanced currents to the local unbalanced load also before the islanding. Thus, the grid is (partially) relieved from supplying unbalanced currents to the unbalance local load.

A comparison of the response in average active power and virtual speed of the VSM after islanding with the unbalanced load is presented in Fig. 10. As shown in the figure, the cases with balanced currents or constant active power are not able to maintain the desired average voltage of the load, which is resulting in reduced power provided to the resistive load. Thus, the frequency droop control is also resulting in a higher steady-state frequency compared to the case when the load voltage is maintained close to the rated value. The case with constant reactive power is instead
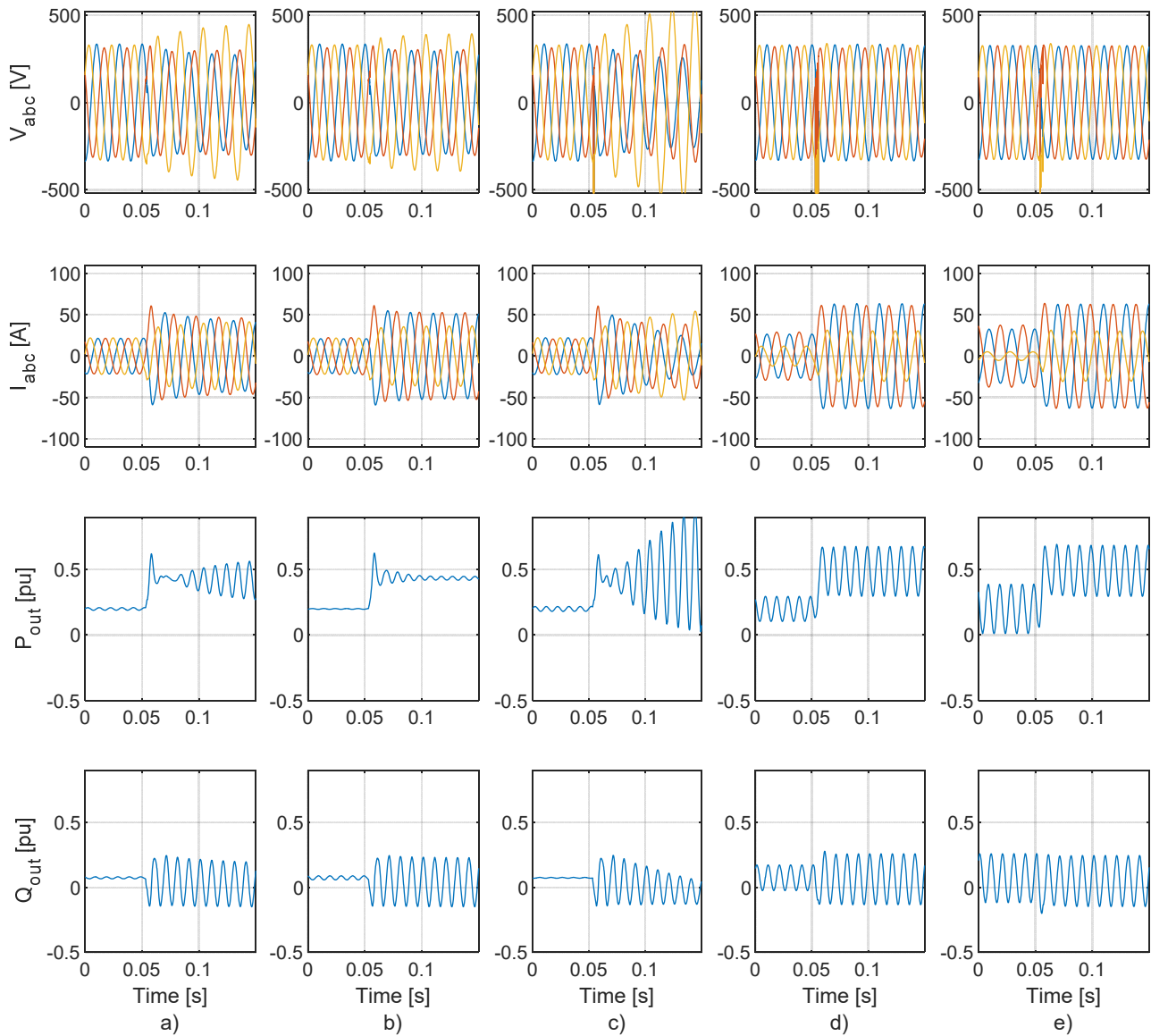
Fig. 9 Simulation results showing the transient response to sudden islanding with an unbalanced load at t=0.05 s a) Balanced currents b) Constant active power, c) Constant reactive power, d) Negative sequence virtual impedance c) Negative sequence voltage controller

resulting in a significant increase of the load power and a corresponding reduction in the steady state frequency. This further confirms how this control strategy is unsuitable for operation in islanded mode.

The case with negative sequence voltage control results in the expected load power of 0.5 pu and a corresponding droop effect in the frequency. The results for the case with only a negative sequence virtual impedance are also very close to the case with closed loop balancing of the voltage.

The general trend of the results in Fig. 10 is confirmed by the results in Fig. 11, which shows the response to a change of the load resistance under unbalanced islanded operation. In this figure, the cases with constant active or reactive power are not included since the operation with these control strategies is clearly unacceptable. A case with the initial balanced load is also included as a point of reference. The figure shows how the case with balanced three phase currents results in a total average load close to the case with balanced loads, since no additional current is provided to the phases with increased load. As in Fig. 10, the load power and the steady-state frequency of the case with negative sequence virtual impedance is almost identical to the case with closed

loop control of the voltage. Indeed, these two strategies are the only cases providing reasonable performance for operation in islanded mode with unbalanced loads.

IV. CONCLUSIONS

This paper has evaluated the options for operating a current controlled Virtual Synchronous Machine (CCVSM) under unbalanced conditions, and the resulting performance in both grid-connected and islanded modes. Five different strategies for controlling the negative sequence currents are identified, and their performance is assessed by time domain simulations. The simulation results clearly show how the control strategies based on calculation of the negative sequence current references for shaping the power flow characteristics are only suitable for grid-connected operation. Thus, if any of these strategies are preferred for grid-connected operation, they should be immediately disabled in case of transitioning to islanded mode. Operation with a negative sequence virtual impedance results in a similar steady-state response to unbalances as would result from a synchronous machine and can ensure stable operation in both grid-connected and islanded operation. However, this approach will not fulfil any specific objectives for shaping
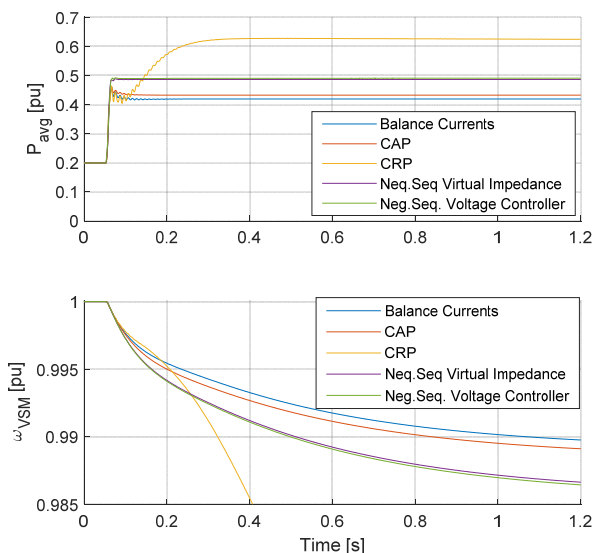
Fig. 10 Comparison of response to the transition from grid-connected operation to islanded mode with an unbalanced load
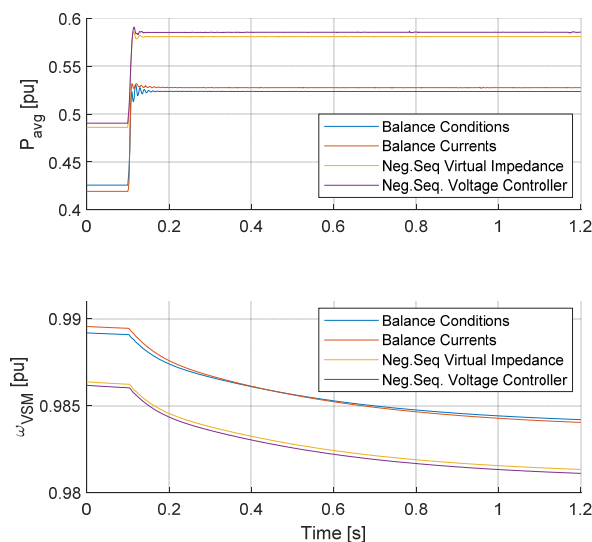

Fig. 11 Response to a step increase of the load by 0.1 pu under unbalanced conditions

the power flow characteristics or balancing of the voltage. Closed loop control of the negative sequence components for balancing the local voltages is suitable for islanded operation with unbalanced local loads. Although this approach also can be utilized for grid-connected operation in weak grids with high equivalent impedance, the controllers will saturate if the system is operated in a strong grid. Thus, there is no universal control strategy that will be suitable for all types of unbalanced operation. Instead, a flexible mechanism for choosing between different objectives depending on the operating conditions, as presented in this paper, can be useful. Further analysis should consider how to adapt the operation of the VSM to any grid-connected or islanded conditions by automatically selecting the proper objective for control of the negative sequence currents.

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