Improving the Power Reference Tracking of Virtual Synchronous Machines by Feed-Forward Control

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***Abstract*—This paper presents a feed-forward control method for improving the power reference tracking performance of Virtual Synchronous Machines (VSMs) without compromising their main features in terms of grid forming capability and inertia emulation. The proposed approach acts directly on the phase angle used for reference frame transformations in the control system and can be generally applied to all VSM-based control schemes relying on a virtual swing equation. A small-signal model of a selected VSM implementation with the proposed feedforward control is derived. This model is utilized to assess the impact of the power reference feedforward on the operational characteristics of the VSM. The improvement of the power reference tracking capability is demonstrated by analysing the transfer function from the power reference to the power injected to the grid, as extracted from the small-signal model. The frequency domain analysis also demonstrates how the oscillation modes of the VSM and the inertial response to grid frequency perturbations remain unaffected by the proposed feed-forward control. Finally, the findings from the frequency domain analysis are verified by time domain simulations.**

Keywords—Feed-forward, Grid Forming Control, Inertia Emulation, Virtual Synchronous Machines

I. Introduction

Control of power electronic converters to provide virtual inertia by emulating the behaviour of synchronous machines has been introduced during the last decades as a potential countermeasure against challenges due to reduced physical inertia in the power system [1]-[6]. In general, two types of control strategies have been proposed for this purpose [7]:

i) Utilization of the estimated grid frequency derivative to emulate the power response that would result from a rotating mass connected to the power system [1]. This approach can be generally labelled as frequency-derivative-based inertia emulation (*df/dt* IE).

ii) Explicit emulation of a virtual swing equation traditionally used to model the inertial dynamics of a synchronous machine [2], [8]. This approach can be implemented in several different ways, but control schemes relying on this approach can be generally referred to as Virtual Synchronous Machines (VSMs).

Inertia emulation strategies based on the *df/dt* IE concept typically rely on established control methods for grid connected converters, relying on synchronization to the grid voltage by a Phase Locked Loop (PLL). Thus, such control strategies inherit the advantages of conventional control methods in terms of fast response and decoupled control of active and reactive power. However, *df/dt* IE strategies can experience stability problems in weak grid conditions and are not applicable for islanded grids since the PLL-based grid synchronization depends on dominating generation units defining the amplitude and frequency of the grid voltage. VSM-based control methods are instead inheriting the general operational flexibility of synchronous machines. Indeed, the power-balance-based grid synchronization mechanism defined by the emulated swing equation implies that such control strategies are directly applicable in islanded grids or other stand-alone power systems. However, the virtual swing equation also implies that the response to variations in the power reference will be determined by the same emulated inertial dynamics that provides virtual inertia to the power system. Thus, VSM-based control methods will have much slower response to power reference variations than *df/dt IE* strategies. This could prevent the adoption of VSM schemes in applications where accurate and fast control of the power is critical.

This paper proposes a power feed-forward (PFF) control method that provides enhanced transient response to changes in the power reference of a VSM. The feed-forward term is implemented as an offset added directly to the phase angle output of the emulated swing equation, which is responsible for the grid synchronization Thus, the proposed implementation of PFF VSMs directly influences the power-angle which determines the steady-state power transfer through the equivalent impedance between the VSM and the grid. Since the feed-forward term is calculated from the power reference, it only influences the response to power reference variations and does not affect the inertial dynamics of the VSM during grid frequency variations. Thus, PFF VSM control can be suitable for converter units where inertia emulation is introduced as an auxiliary function while still having another primary purpose depending on direct control of the active power flow. This can, for instance, include energy storage systems, wind turbines where the rotor energy can be utilized for providing inertial response to the power system, or power-controlled HVDC converter terminals.

To demonstrate the benefits and the performance of the proposed PFF VSM control, a numerical analysis is conducted for an example of a VSM scheme modified with the addition of the power feedforward. For this purpose, a Current Controlled VSM (CCVSM) with inner loop current controllers and a quasi-stationary model of the stator impedance in a synchronous machine is introduced from [9]. A detailed small-signal state-space model including all

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elements of the assumed control system is then developed. The transfer functions characterizing the power exchange with the grid as a function of the power reference and of the grid frequency are derived and analysed. The results clearly demonstrate that the proposed feed-forward control does not influence the disturbance response characteristics and the inertia emulation functionality of the VSM while it significantly improves the tracking capability with respect to the power reference. These results from the analytical evaluations are verified by time-domain simulations.

II. Power-Angle Feed-Forward for Improved Power Reference Tracking of VSM-based Control

Although a wide range of implementations have been proposed for VSM-based control of power electronic converters, a shared feature of such control schemes is the emulation of the rotor dynamics of a synchronous machine (SM) [7]. The simplest and most common approach for emulating the SM inertial dynamics is the implementation of a virtual swing equation (SE). As outlined in the following, the basic form of the VSM SE and the corresponding quasi-stationary power transfer characteristics will determine the VSM response to changes in the power reference. This explanation serves as a basis for introducing the proposed concept of power feed-forward control to improve the reference tracking capability of VSM-based control schemes.

A. The Virtual Swing Equation of VSM-based Control

The general form of a virtual SE for VSM-based control can be identical to the traditional swing equation (SE) of an SM [7], and can be expressed in per unit quantities as:

$$\frac{d\omega_{VSM}}{dt} = \frac{p_m}{T_a} - \frac{p_o}{T_a} - \frac{k_d \cdot (\omega_{VSM} - \omega_g)}{T_a} \quad (1)$$

where ω_{VSM} is the virtual speed of the emulated SM dynamics. Furthermore, p_m represents the emulated mechanical input power to the swing equation, p_o is the electrical output power, while T_a (= 2H) is the mechanical time constant representing the emulated inertia. The grid frequency ω_g is assumed to be known, although in practical implementations it is commonly set to a constant value or estimated, for instance by a PLL [4], [10]. The damping is then defined by the difference between ω_{VSM} and ω_g multiplied by the damping coefficient k_d [7].

For VSM-based control, the virtual swing equation provides a power-balance-based grid synchronization mechanism for the converter. Thus, the instantaneous phase angle θ_{VSM}, used for reference frame transformations in a VSM-based control system is defined by:

$$\frac{d\theta_{VSM}}{dt} = \omega_{VSM} \cdot \omega_b \quad (2)$$

where $\omega_b = 2\pi f_b$ is the base value for the angular frequency, corresponding to the nominal operating frequency.

For simplified phasor-based calculations of power flow, and for time-invariant modelling, the instantaneous phase angle from (2) cannot be directly applied. Instead, the relative phase angle displacement between the reference frame orientation of the VSM control system and the equivalent grid voltage must be utilized. This phase angle corresponds to the power angle δ, as defined by:

$$\frac{d\delta}{dt} = \left(\omega_{VSM} - \omega_g\right) \cdot \omega_b \quad (3)$$

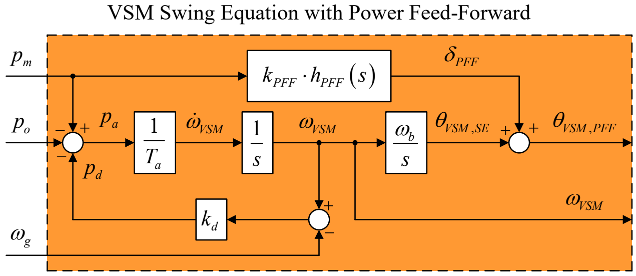

Fig. 1. Virtual Swing equation of Virtual Synchronous Machine with added Power Feed-Forward (PFF)

Assuming the impedance defining the power flow between the VSM and the grid to be purely inductive, the electrical output power p_o can be directly approximated by the traditional simplified power flow equation [11], given by:

$$p_o \approx \frac{\hat{v}_e \hat{v}_g}{x_{tot}} \sin\delta \quad (4)$$

where $\hat{v}_e$ is the internal voltage amplitude of the VSM, $\hat{v}_g$ is the amplitude of the grid voltage and the power angle δ is defined by (3). The total reactance x_{tot} can include the equivalent inductance of the power system as well as any virtual inductance included in the VSM implementation.

B. Dynamic limitations of VSM-based control schemes

The main purpose of the emulated SE in a VSM is to provide a power-balance-based synchronization mechanism and an inertial response to disturbances in the grid frequency. However, these functions also determine the general dynamics of SE-based VSM implementations. Indeed, the virtual SE implies that the VSM response to power reference variations will be determined by the emulated inertial dynamics, equivalently to an SM. Considering for instance the transfer function between the input power p_m and the emulated frequency, which can be easily derived from (1) as:

$$\frac{\omega_{VSM}(s)}{p_m(s)} = \frac{1}{k_d + T_a s} \quad (5)$$

it is clearly seen that the inertia constant T_a and the damping k_d will influence the dynamic response. Thus, the power reference tracking capability of the VSM will be determined by the emulated inertial dynamics and will be reduced when increasing the emulated inertia. This implies that the higher the emulated inertia, the more difficult it will be to control the power flow of a VSM for other purposes than the inertia emulation. This could become critical if the VSM is implemented in an application where the tracking of the power would require larger bandwidth as for example in wind turbines or HVDC terminals.

C. Proposed Power Feed-Forward (PFF) Strategy

For improving the dynamic response of the power control, and thereby the power reference tracking capability, of a VSM, a power feed-forward (PFF) strategy is proposed in this paper. The strategy is illustrated in Fig. 1, which shows the block diagram of the virtual swing equation defined by (1) and (2) with the addition of a feed-forward term δ_{PFF} which is added directly to the phase angle signal $\theta_{VSM,SE}$ from the virtual swing equation. The feed-forward term could be ideally calculated from (4) as:

$$\delta_{PFF} = \sin^{-1}\left(p_o^* \frac{x_{tot}}{\hat{v}_e \hat{v}_g}\right) \quad (6)$$

Assuming relatively small variations in the total power angle, this expression can be simplified to (7):

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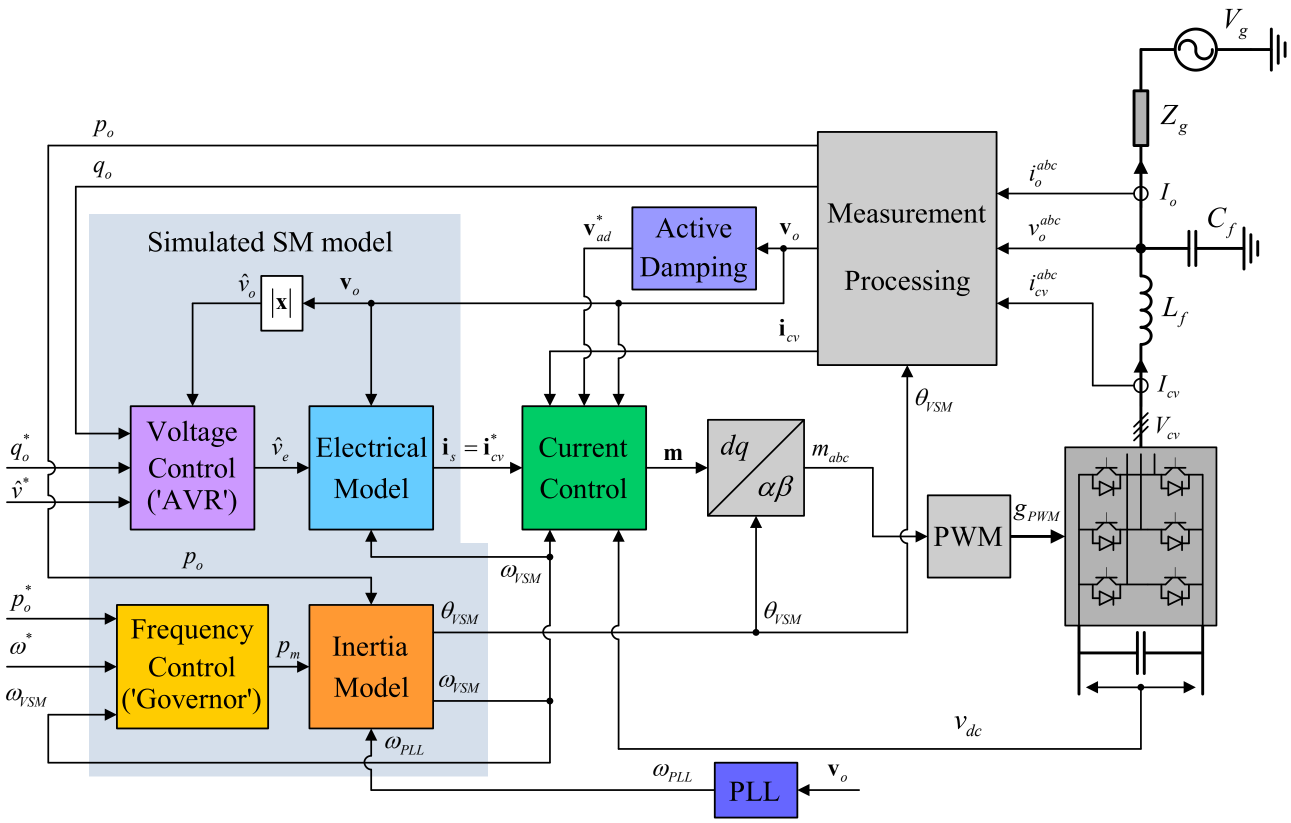

Fig. 2. Control structure of Current Controlled Virtual Synchronous Machine (CCVSM) used for evaluating the performance with Power Feed-Forward (PFF)

$$\delta_{PFF} \approx p_o^* \frac{x_{tot}}{\hat{v}_e \hat{v}_g} = k_{PFF}\, p_o^* \tag{7}$$

A transfer function $h_{PFF}(s)$ can also be included in the feed-forward path to shape or smooth the phase-angle signal to avoid sudden phase jumps in the control of the converter. In the following, it is assumed that $h_{PFF}(s)$ is a first order low-pass filter with a small time constant that has negligible impact in the frequency range of the inertial dynamics.

It should be noted that the feed-forward concept introduced in Fig. 1 is general and independent on the specific VSM implementation. Thus, the PFF can be applied independently of whether inner current and/or voltage control loops are included in the VSM control system.

From simple manipulations of the block diagram in Fig. 1 combined with utilization of (4), it can be found that an ideal feed-forward of the power angle δ_{PFF} could imply an instantaneous response of the VSM-based control system to a change in the power reference. However, without the feed-forward term, the dynamic response to power reference variations will be determined by the inertial dynamics of the emulated swing equation. Thus, the proposed concept should effectively improve the power reference tracking capability of the VSM. At the same time, it can be observed from the block diagram that transfer function between the grid frequency and the VSM frequency will not be influenced by the feed-forward term. Thus, the inertial dynamics of the VSM in response to grid frequency variations will not be affected by the PFF control. These considerations will be further evaluated and demonstrated in the following.

III. VSM Example for Analysis of VFF Performance

For assessing the performance of the PFF function, a current controlled VSM (CCVSM) with a quasi-stationary electrical model (QSEM) as described in [9] will be assumed as a reference. This control scheme will be evaluated in a simple configuration with a voltage source converter (VSC) connected via an LCL filter to an equivalent grid model represented by a voltage source behind an impedance.

A. Control Strategy for evaluation of VSM with PFF

An overview of the control structure of the applied CCVSM QSEM and the studied system is presented in Fig. 2. The control system is based on an inner loop current controller, with conventional decoupled PI regulators in a synchronously rotating reference frame (SRRF). The synchronization to the grid voltage and the corresponding phase angle used for reference frame transformations are defined by the speed and position of the emulated inertia model, according to Fig. 1. The performance will then be evaluated with or without the PFF-function activated.

Beyond the PFF-function, the main elements of the CCVSM implementation are directly based on [9]. Thus, the reference signals for the current controllers are obtained as:

$$\mathbf{i}_s^{QSEM} = \frac{\hat{v}_e - \mathbf{v}_m}{\left(r_s + j\cdot\omega_{VSM} l_s\right)} \tag{8}$$

which represents a quasi-stationary emulation of the armature windings of an SM. Thus, r_s and l_s are the virtual stator resistance and stator inductance, respectively, while $\boldsymbol{v}_m$ ($= v_{m,d} + j\, v_{mq}$) is the filtered voltage measurements at the capacitor-side of the primary filter inductance of the VSC. Differently from [9], the internal voltage amplitude $\hat{v}_e$ of the VSM is generated by a reactive power droop function as :

$$\hat{v}_e = \hat{v}^* + k_q\left(q^* - q_m\right) \tag{9}$$

where $\hat{v}^*$ is the voltage reference, q^* is the reactive power reference, q_m is the measured reactive power flow, and k_q is the reactive power droop gain [10]. It should be noted that a

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TABLE I
PARAMETERS AND SET-POINTS

Parameter	Value	Parameter	Value
Rated voltage $V_{S,LL,RMS}$	690 V	Current controller gain: k_{pc}, k_{ic}	1.27 15
Rated power S_b	2.75 MVA	Voltage feed forward in current controller k_{ffv}	0
Rated ang. freq. ω_b	$2\pi\cdot 50$ Hz	Active damping gain k_{AD}	1.5
Grid voltage $\hat{v}_g$	1.0pu	Active damping ω_{AD}	20 rad/s
Grid angular frequency ω_g	1.0 pu	Frequency controller gain k_ω	10
Grid inductance l_g	0.50 pu	PLL PI controller gain, $k_{p,PLL}$, $k_{i,PLL}$	0.084 4,69
Grid resistance r_g	0.005 pu		
Filter inductance l_f	0.08 pu	PLL voltage filter, ω_{PLL}	500 rad/s
Filter resistance r_{lf}	0.003 pu	Reactive power filter ω_{qf}	200 rad/s
Filter capacitance c_f	0.074 pu	Voltage reference $\hat{v}^*$	1.0 pu
Inertia constant T_a	1 & 10 s	Reactive power ref. q^*	0.0 pu
Damping coefficient k_d	40	Reactive power droop gain k_q	0.0 pu
SM inductance l_s	0.25 pu	Power reference p^*	0.0 pu
SM resistance r_s	0.04 pu	Frequency ref. ω^*_{VSM}	1.0 pu

low-pass filter is included in the measurement of the reactive power.

Another small difference from [9] is that a PLL is assumed for detecting the grid frequency which is used in the implementation of the damping of the virtual swing equation according to Fig. 1, as described in [10]. It can also be mentioned that the "Governor" function indicated in Fig. 2 is a power-frequency droop, as defined by:

$$p_m = p_o^* + k_\omega \cdot (\omega_{VSM}^* - \omega_{VSM})\,. \quad (10)$$

B. State-space modelling

For further evaluation of the CCVSM structure with or without the PFF control, a mathematical model of the system from Fig. 2 has been developed in state space form. The model is developed from [9] by introducing the PFF term in the phase angle used for reference frame transformations and by including the modifications mentioned in the previous section. The PLL, which was not included in [9], is modelled as discussed in [10]. The resulting non-linear state-space equation is expressed as:

$$\dot{\mathbf{x}} = f\left(\mathbf{x},\mathbf{u}\right) \quad (11)$$

where $\mathbf{x}$ is the vector of states while $\mathbf{u}$ is the vector of input signals. The developed model has 23 states and 7 inputs and can be directly linearized for the purpose of frequency domain analysis. The resulting linearized model is expressed on general state-space form as:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\left(\mathbf{x}_0,\mathbf{u}_o\right)\Delta\mathbf{x} + \mathbf{B}\left(\mathbf{x}_0,\mathbf{u}_o\right)\Delta\mathbf{u}\\ \mathbf{x}\left(t\right) &= \mathbf{x}_0 + \Delta\mathbf{x}\left(t\right)\end{aligned} \quad (12)$$

In the following, the linearized model will be validated and utilized for evaluating the frequency domain characteristics of the evaluated CCVSM with and without the PFF function.

IV. VALIDATION OF THE SMALL-SIGNAL MODEL

The developed small-signal state-space model has been validated by comparing its response with the time domain simulation of a corresponding non-linear model in Simulink. For this purpose, the parameters listed in Table I have been applied, with the PFF function of the CCVSM activated. The comparison of the step response of the virtual speed ω_{VSM} to a change of 10% in the power reference power is shown in Fig. 3. As the plotted curves are identical, the figure highlights how the linearized model can accurately represent

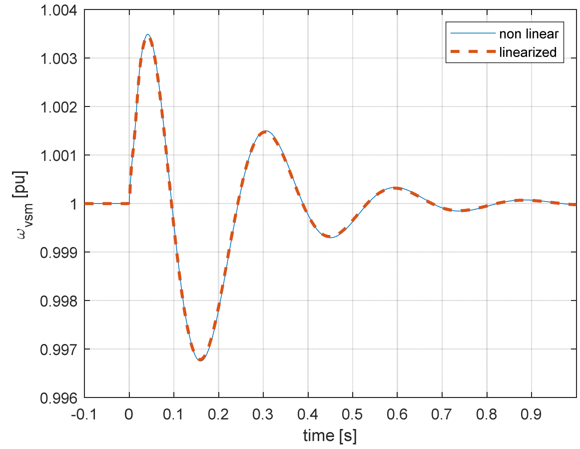

Fig. 3. Verification of the linearized model for a step in the power reference

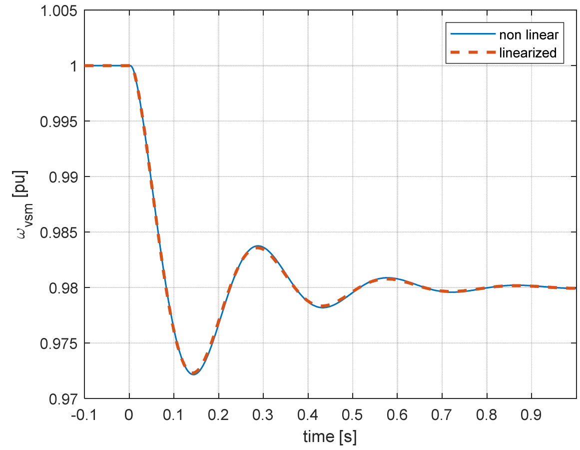

Fig. 4. Verification of the linearized model for a step in the grid frequency

the dynamics of the detailed model even for a relatively large variation in the reference power. Similarly, the response to a 2% step in the grid frequency is shown in Fig. 4. Although a very small deviation between the models can be noticed around the peaks of the frequency oscillation, the results clearly demonstrate the validity of the linearized model for analysing the small-signal dynamics of the studied system. Thus, frequency-domain analysis of the developed model can be utilized for evaluating the performance characteristics of the proposed PFF control.

V. NUMERICAL ANALYSIS OF PFF VSM PERFORMANCE

This section aims at providing a numerical assessment of the benefits of the PFF in a VSM-based control structure compared to a conventional implementation where the power reference tracking is fully determined by the emulated swing equation. Moreover, the numerical results are intended to validate that the PFF does not affect the response of the VSM to perturbations of the grid frequency and thereby do not compromise inertia emulation characteristics of the VSM.

A. Eigenvalue-based analysis

The eigenvalues of the linearized system can be calculated directly from the **A**-matrix to identify the modes of the evaluated model. An example of results from eigenvalue analysis is shown in Fig. 5, where the effect of the inertia on the modes of the system is studied by changing the value of T_a between 1 s and 10 s. The poles are all with negative real part indicating a stable system for each inertia

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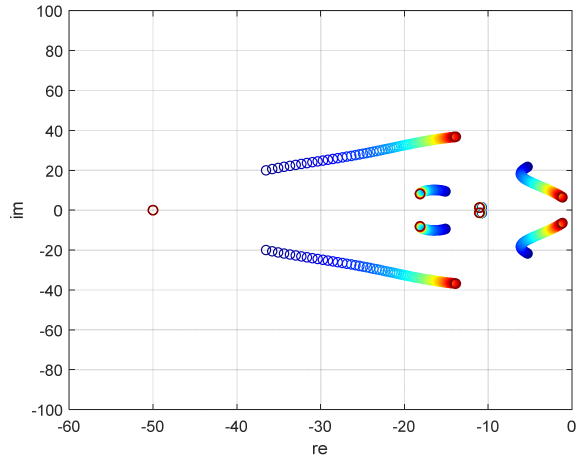

Fig. 5. Eigenvalues with real part above -60 for inertia time constant ranging between 1 s (blue) and 10 s (red)

value. The figure indicates only the poles with real part higher than −60. A few additional poles are excluded from the figure, but they are associated to fast dynamics and did not exhibit any influence from the inertia value. The results in Fig. 5 show how an increasing value of the emulated inertia is leading to a longer settling time of two of the modes of the system. These results are obtained with the PFF function activated, but the same results are obtained if the PFF gain k_{PFF} is set to zero (i.e. when disabling the PFF). The reason is that the parameters of the PFF do not appear in the A-matrix of the small signal model. Thus, since the PFF parameters are present only in the B-matrix, the proposed strategy will only influence the input-output characteristics of the system. This confirms the initial assumption that the proposed strategy for improving the reference tracking capability of the VSM should not influence the oscillation modes or the corresponding response to perturbations in the grid frequency.

B. *Transfer function-based analysis*

To evaluate the input-output characteristics of the evaluated system in the frequency-domain, the transfer functions from the power reference or the grid frequency to the power injected by the VSM to the grid have been extracted from the small-signal model. This allows for evaluating the impact of the PFF function in comparison to a VSM with a traditional swing equation without PFF. Two cases characterized by different values for the virtual inertia are considered, corresponding to values of T_a equal to 1 s and to 10s.

A Bode magnitude plot of the transfer function from the active power reference to the resulting active power injected to the grid, i.e. $h_{p*,p}(s) = p_o(s)/p_o^*(s)$, is shown in Fig. 6 . The figure shows the amplitude of the transfer function for four cases, with and without PFF for the two evaluated values of T_a. Activating the PFF clearly increases the bandwidth of the VSM for tracking the power reference for both values of inertia. Indeed, with the PFF, the transfer function amplitude crosses the unity gain line at around 70 Hz before decaying linearly, independently of the emulated inertia. However, for the cases without the PFF, the crossover frequency is reduced to about 5 Hz with $T_a = 1$ s, and less than 1 Hz with $T_a = 10$ s. Indeed, the inertia acts as a low pass filter for the power reference and a higher value of the inertia leads to a slower response to changes in the power reference. The PFF effectively bypasses the inertia, leading to a faster response

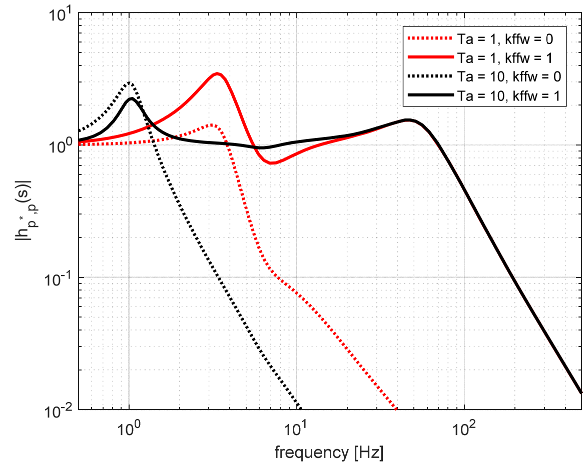

Fig. 6. Amplitude of the transfer function from power reference to power

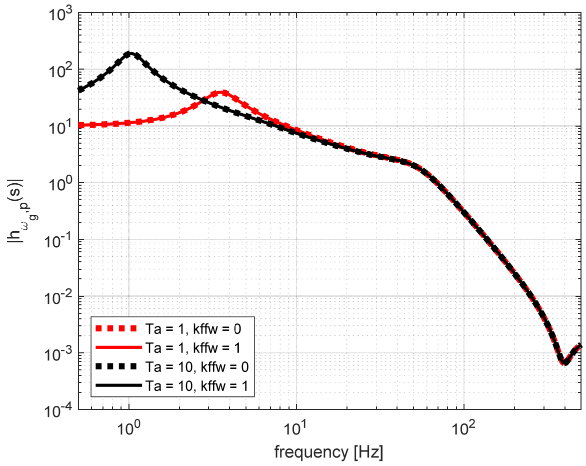

Fig. 7. Amplitude of the transfer function from grid frequency to power

and better reference tracking capability in a wider frequency range. It should be noticed that all the transfer functions show resonances in the form of peaks in the amplitude between 1 and 10 Hz. Higher peaks are undesirable because this can lead to amplification of frequency components and corresponding oscillations. The feed-forward in the case with a low value of T_a presents a higher resonance peak compared to the scheme without feedforward while the situation is reversed in the case with higher virtual inertia. This implies that for lower values of virtual inertia, the feedforward can increase the bandwidth and the general responsiveness of the control in tracking references but with a drawback in terms of higher overshoot and oscillations. However, for high values of the virtual inertia the feedforward does not bring penalties in terms of amplified oscillations and higher overshoots. This is an advantageous feature since it is in case of high T_a that the performance improvement offered by the PFF will be most important.

The Bode magnitude plot of the transfer function from the grid frequency to the active power injected to the grid, i.e. $h_{\omega g,p}(s) = p_o(s)/\omega_g(s)$, is shown in Fig. 7. The curves with and without the PFF are overlapping, confirming that the feedforward does not affect the characteristics of the VSM scheme for disturbances in the grid frequency. This implies that the PFF has no effect on the power synchronization mechanism and the grid forming capabilities. The figure also shows how the emulated inertia influences the frequency and the amplitude of the resonance peak of the transfer function. Indeed, a higher value of T_a implies a stronger reaction in terms of power injected during a frequency disturbance, but

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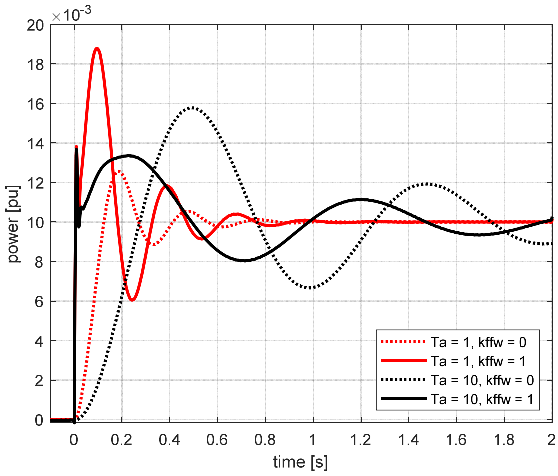

Fig. 8. Time domain response to a step in the power reference

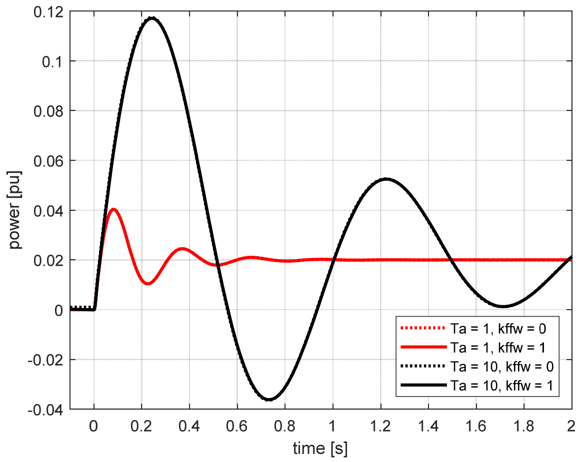

Fig. 9. Time domain response to a step in the grid frequency

also corresponds to a lower characteristic oscillation frequency of the inertial dynamics.

C. *Time-domain analysis*

The control scheme has been simulated in the time domain to verify the response to a change in the power reference or to a frequency perturbation in the grid. The response to a step change in the power reference of 1% is shown in Fig. 8. The PFF clearly increases the responsiveness of the VSM since the rise time is much smaller. It can be also noticed that the rise time is not affected much by the inertia value as indicated from the considerations on the bandwidth for the associated transfer function. The rise time and the slope for the schemes without PFF is slower and more dependent on the emulated inertia value with higher values of T_a associated with slower rise time. The observations regarding the peak amplitude of the transfer functions and the presence of resonances are further verified in the time domain. Indeed, for $T_a = 1$ the scheme with PFF shows a higher overshoot and more pronounced oscillations than without the PFF, while for the value of $T_a = 10$ the PFF scheme presents advantages both in terms of increased responsiveness and reduced oscillations.

The time domain response to a step perturbation in the grid frequency equal to $-2\ 10^{-3}$ pu is shown in Fig. 9. In this case the presence of the feedforward term does not alter the time domain response, and the curves are perfectly overlapping. The impact from the emulated inertia is instead quite significant since the higher value of inertia leads to a much higher reaction and overshoot and to a much lower frequency of the oscillatory mode, as expected from the frequency-domain analysis.

VI. Conclusion

This paper has presented an approach for improving the power reference tracking performance of VSM based control schemes relying on a simulated swing equation. The improved response is obtained by adding a power feedforward (PFF) term directly to the phase angle resulting from the swing equation utilized for inertia emulation and power-balance-based grid synchronization. However, the feedforward term does not affect the modes of the system and the response to grid disturbances. Thus, the PFF does not alter the stability characteristics, the power synchronization mechanism or the grid forming capabilities of the VSM. The increased bandwidth for reference tracking and the higher responsiveness can be necessary to provide grid forming capabilities offered by the VSM while preserving controllability of the power injected in the grid. Examples of applications could be wind farms or HVDC terminals.

The validity of the feedforward term in increasing the tracking capabilities without affecting the response to grid disturbances is proven by frequency domain analysis of a small-signal model and by numerical simulations. These results confirm that rise time and tracking bandwidth are increased as intended. However, the feedforward could amplify oscillations and lead to higher overshoots in case of low inertia. Thus, the PFF control should be considered depending on system requirements and emulated inertia, and will be most relevant when high virtual inertia is needed.

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