Dynamic Voltage Stiffness Control Technique for a Virtual Oscillator-Based Grid-Forming Controller

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Abstract—Voltage stiffness is a vital parameter for grid-forming inverters. With a very high voltage stiffness, an inverter picks up all the reactive power demands of the point of common coupling. In contrast, with a very low voltage stiffness, the inverter does not participate in voltage regulation at all. Hence, any grid-forming controller should be able to control voltage stiffness dynamically. Virtual oscillator-based controllers (VOCs), the latest and most advanced grid-forming controllers, provide all the steady-state functionalities of the conventional droop controllers and, in addition, time-domain synchronization with a connected network. However, existing VOCs cannot control voltage stiffness dynamically. As a result, limiting reactive power output during a higher voltage sag, especially when connected to a weak grid, is challenging for VOCs. The only existing solution for a VOC in such conditions is to enter into current control mode, which leads to ineffective synchronization, output power oscillation, and, finally, inefficient grid-forming operation. Integrating a dynamic voltage stiffness controller inside a VOC is not as straightforward as a droop controller. Because, unlike phasor-based droop controllers, VOCs have time-domain implementation. In this article, we introduce virtual impedance-based dynamic voltage stiffness control technique for VOCs with systematic design procedures and rigorous stability analysis.

Index Terms—Grid-forming controller, virtual oscillator controller (VOC), voltage stiffness control, weak grid.

I. INTRODUCTION

VirtUal oscillator (VO) based controllers (VOCs) are time-domain-based grid-forming controllers [1], [2]. VOCs outperform their phasor-based counterparts, i.e., conventional droop controllers and virtual synchronous machine (VSM) controllers, in many important performance parameters, which are as follows.

Conventional droop and VSM controllers work on phasor-based ac parameters defined properly only in sinusoidal steady state [3]. On the contrary, VOCs can achieve asymptotic stability and global synchronization from an arbitrary initial condition by using only locally available time-domain parameters as feedback [4]. At the same time, VOCs meet all the steady-state functionalities of droop controllers [4], [5]. Under a wide range of voltage and frequency regulations and large grid disturbances, VOCs perform better than conventional droop controllers when compared in terms of time-domain responses [5], [6]. By adopting a time-domain implementation, VOCs outperform the conventional droop and VSM controllers in critical performance parameters, such as rise time, settling time, and steady-state error [3], [7].

The usability of VOCs is significantly improved by recent research works [8], [9], [10], which have provided a very general VO-based control architecture to include crucial system-level functionalities, such as fault ride-through capability and maximum power point tracking (MPPT) capability.

However, the existing literature on VOCs does not consider the aspect of dynamic voltage stiffness control, an important parameter for any grid-forming inverter, especially when connected to a weak grid [11]. Commonly, a VOC is designed for less than a 10% tolerable voltage sag range [12].

During the addition of a large load in an electrical network, the grid-forming inverter, which is electrically nearest, is affected first [11], [13]. If the connected grid is weak, the voltage drop becomes large. Hence, the reactive power demand on the nearest grid-forming inverter becomes significantly high. At this point, if the voltage stiffness of the grid-forming inverter is too low, the inverter does not participate in voltage regulation at all [11]. As the grid is weak, the voltage amplitude drops further. On the other hand, if the voltage stiffness of the inverter is too high, the inverter picks up all the reactive power demand on itself [11], and the output current may tend to exceed the maximum rating. When the output current tends to the limit, the existing VOCs have two options. The first option is to be disconnected from the electrical network. However, the new grid codes prevent grid-forming converters from being disconnected easily from the network in such a condition as mentioned above [14]. The second option is to enter into the current control mode by activating the fault ride-through controller [8], [15]. However, the effective synchronization of a grid-forming controller with the connected network gets severely affected in the current control mode leading to a large output power oscillation [11]. The exact reason behind the loss of synchronization of a VOC in the current control mode is investigated using a simulation study in Section V.

From the above paragraph, it is clear that the existing VOCs need to integrate dynamic voltage stiffness control to improve the system-level usability further. However, it is more difficult...
to incorporate dynamic voltage stiffness control in VOCs than the conventional droop or VSM controllers for the following reasons.

1) Integrating a voltage stiffness control loop in droop and VSM controllers is straightforward due to the phasor-based implementation of the mentioned controllers. Even a single cascaded multiplication block (which includes virtual impedance (VIm) coefficients) can incorporate the voltage stiffness control in a droop controller [13]. However, the time-domain implementation makes it difficult to incorporate the voltage stiffness control in VOCs.

2) Unlike the conventional droop controllers, the reactive and active power droop characteristics of VOCs are not decoupled. The reactive power droop of an existing VOC cannot be changed independently without affecting the active power droop.

3) The nonlinearity in the reactive power droop characteristic of a VOC makes it more challenging than droop controllers to design the voltage stiffness control parameters. In addition, due to the same reason, finding the limiting values of the control parameters is also more difficult.

The implementation technique for dynamic voltage stiffness control in a phasor-based (droop and VSM controllers) and time-domain-based (VOCs) grid-forming controller differs significantly. However, the concept and analogy used in the earlier literature to incorporate voltage stiffness control in the conventional droop and VSM controllers are very valuable for VOCs to incorporate the same.

The earlier literature shows that the VIm method is the key to achieve dynamic control over the voltage stiffness of a grid-forming inverter [16]. Next, the system requirements are divided into two categories to better understand the mapping between the requirements and the existing designs.

In the first category, the controller must ensure safety by limiting output current during fault conditions. It is relevant to mention that according to IEEE Standard 519-2014, the maximum allowable voltage sag in an electrical power system is commonly considered to be 20%. Hence, a phase with a 20% lower voltage amplitude than the rating can be regarded as faulty by the system operator. In such a condition, the converter can enter into the current control mode from the grid-forming mode [17], [18], [19].

In the second category, the inverter must stay in grid-forming mode during a voltage sag or grid disturbance that is not as high in amplitude to be considered a fault by the system operator. It is relevant to mention that typical voltage sags (10%–20%) frequently occur in power systems [20]. The reactive power demand on a grid-forming inverter increases with a decrease in the voltage amplitude of the PCC. The key here is to modify the droop characteristic of the inverter using VIm [13]. The grid-forming mode is maintained because the current output of the inverter is lowered by adjusting the reactive power droop characteristic (Q–V droop), which prevents the activation of the saturation and antiwindup controller of the current control loop. Maintaining grid-forming operations during balanced or unbalanced voltage sag (i.e., high reactive power demand) helps to achieve different objectives, such as the improvement of reactive power-sharing accuracy among parallely connected grid-forming inverters [21], [22], [23] and mitigating voltage unbalances in the islanded microgrid [24], [25].

The concept of VIm-based voltage stiffness control is well established for phasor-based grid-forming controllers, i.e., conventional droop controllers and VSM [13], [26]. This article has presented the systematic implementation of a VIm-based dynamic voltage stiffness controller for time-domain-based grid-forming controller, i.e., VOCs using critical design procedure and analysis. The discrete research contributions of this article are summarized as follows.

1) The implementation technique for the VIm-based voltage stiffness controller is available in the literature only for phasor-based grid-forming controllers. This article has introduced a systematic implementation technique for a VIm-based dynamic voltage stiffness controller for time-domain-based grid-forming controllers (i.e., VOCs). It is important to mention here that the concept of the system-level architecture of VOCs is leveraged from our previous work [10] in the above-mentioned proposed implementation technique.

2) The proposed dynamic voltage stiffness controller is designed in such a way that it can be integrated into an existing VO-based system-level grid-forming controller without the requirement of any change in the existing controller or any extra sensor, as shown in Fig. 1.

3) This article has introduced a crucial design procedure for selecting the values of the parameters of the proposed dynamic voltage stiffness control loop for VO-based controllers. The proposed design procedure successfully works for nonlinear reactive power droop characteristics of VOCs.

4) A small-signal stability analysis is presented to calculate the limiting values of the control parameters. A detailed model of the VO-based grid-forming controller, nested voltage and current loops, the connected power system, and the proposed controller is considered for the stability analysis.

5) A brief overview is presented in the conclusion part of this article on how the present research work will be extended in the future to incorporate newer functionalities in VOCs, such as improvement in reactive power sharing among parallely connected converters.

II. PROPOSED VOLTAGE STIFFNESS CONTROLLER

The proposed dynamic voltage stiffness controller is integrated into the existing VO-based system-level grid-forming controller [10], as shown in Fig. 1. The proposed controller is indicated using red lines and words. The existing grid-forming controller is presented in detail in [10]. The proposed controller consists of four main functional building blocks as follows:

1) the symmetrical component-based virtual oscillator controller (S-VOC);
2) nested voltage and current control loops;
3) reference frame transformation blocks;
4) feedback estimator to ride through an unbalanced fault.

The S-VOC provides time-domain synchronization with the positive-, negative-, and zero-sequence voltages of a connected electrical network simultaneously. The S-VOC also provides the positive-, negative-, and zero-sequence droop functionalities.

An individual nested (voltage and current) control loop is dedicated to each phase to decouple control over the phases. Decoupling control is also included over the direct and quadrature axis. Proportional–integral (PI) controllers are used to regulate the voltages of the PCC (capacitor voltages) \(v_{PCC_{abc}}\) and the inductor currents \(i_{L_{abc}}\).

The nested voltage and current controllers work in the synchronous reference frame. Reference frame transformation blocks are required to integrate the synchronous reference frame-based nested controllers with time-domain-based S-VOC.

The feedback estimator helps to retain synchronization during an unbalanced fault condition.
The proposed dynamic voltage stiffness controller is intended to meet the following objectives.

1) The voltage stiffness of a grid-forming inverter should be lower when the reactive power demand on the inverter is low. Conversely, the voltage stiffness should be dynamically increased with the increase in the reactive power demand on the inverter.

2) Active power demand should not have any effect on the voltage stiffness.

To meet the objectives mentioned above, the VIm $Z_{\text{VImabc}}$ is dynamically varied with quadrature-axis inverter current $I_{\text{invqabc}}$ as follows:

$$Z_{\text{VImabc}} = (R_{V0} + mI_{\text{invqabc}}) + j(X_{V0} + nI_{\text{invqabc}})$$  \hspace{1cm} (1)

where $R_{V0}$ and $X_{V0}$ are the initial virtual resistance and reactance, respectively. The parameters $m$ and $n$ are the dynamic virtual resistance and reactance gain, respectively.

A. Selecting the Value of $R_{V0}$, $X_{V0}$, $m$, and $n$

The values and the ratio of the values of $R_{V0}$, $X_{V0}$, $m$, and $n$ can be used to meet different objectives, such as modifying the droop characteristics or the effective $X/R$ ratio from the source side of an inverter [13]. Also, the mentioned values influence the dynamic response of the inverter by modifying the resultant resistance and inductance. An optimal system can be achieved by selecting proper values for the mentioned parameters [26]. Therefore, the calculation of the value of $R_{V0}$, $X_{V0}$, $m$, and $n$ depends on the desired objectives. However, in this article, the mentioned parameters serve only one purpose. The purpose is to dynamically vary the effective VIm $Z_{\text{VIm}}$ with reactive power output.

The initial virtual resistance and reactance $R_{V0}$ and $X_{V0}$ are more important for improving reactive power-sharing accuracy among the inverters in islanded microgrids [13]. Since this article focused on the voltage stiffness control in dispatchable mode, the initial resistance and reactance are taken as zero

$$R_{V0} = 0, \quad X_{V0} = 0.$$  \hspace{1cm} (2)

Next, to design the value of $m$ and $n$, a few constraints should be considered. The values should be lower than the limiting value to ensure stability [19], [26]. Also, if the VIm has a significant dominance over physical impedance, the ratio of $m$ and $n$ should ensure a high resultant $X/R$ ratio.

In the proposed dynamic voltage stiffness controller, the value of VIm parameters is much lower than the limiting values and the physical impedance in the operating range. Therefore, the method adopted in [13] to choose the ratio of $m$ and $n$ for practical implementation in a grid-connected system is followed. In the mentioned method, the value of $m$ and $n$ is taken equally as follows:

$$m = n = k_{\text{VIm}}.$$  \hspace{1cm} (3)

As a result, the mathematical calculation is simplified. By designing the value of one parameter, i.e., dynamic VIm gain $k_{\text{VIm}}$, the dynamic voltage stiffness characteristic of a grid-forming inverter can be controlled. It no longer requires calculating the value of $m$ and $n$ separately.

B. Selecting the Value of $k_{\text{VIm}}$

To design the value of $k_{\text{VIm}}$, it is important to derive the mathematical expression that quantifies the effect of $k_{\text{VIm}}$ on the $Q/V$ characteristic of the S-VOC.

As shown in Fig. 1, the S-VOC is the primary element of the grid-forming system-level controller. The S-VOC provides time-domain synchronization and droop functionalities. The detailed modeling and analysis of the S-VOC are presented in our previous works [10], [27]. The active and reactive power droop characteristic of an S-VOC is derived in [27]. The droop characteristic ($\omega \sim P$ and $Q \sim V$) of the time-domain-based S-VOC is derived in the phasor domain using time averaging and presented as follows:

$$\omega_{\text{abc}} = \omega_n - \frac{k_n k_i}{CV_{abc}^2} (P_{abc} - P_{abc}^*)$$  \hspace{1cm} (4)

$$0 = \frac{\xi}{k^*} V_{abc} (2V_n^2 - 2V_{abc}^2) - \frac{k_n k_i}{CV_{abc}} (Q_{abc} - Q_{abc}^*)$$  \hspace{1cm} (5)
can be modified only by changing the current scaling factor $k_i$, i.e.,

$$Q_{\text{abc}} = Z_{abc}V_{abc}$$

is achieved by selecting an optimal value of voltage sag limit and the decrease in the reactive power output increases. A proper tradeoff between the increase in tolerable limit by reducing reactive power output when the voltage sag

The reactive power droop characteristic effectively only at the region near the nominal voltage, the VIm does not influence the active power droop characteristic.

however, changing the value of $k_i$ simultaneously affects the power system and the controller are included. The output phase voltages (i.e., $V_{\text{abc}}$) of the S-VOC are taken as the reference for the same individual phase for the instantaneous to synchronous reference frame transformation, as shown in Fig. 3. The instantaneous and phasor-domain-based parameters are denoted by small and capital letters, respectively, throughout this article. The detailed derivation of the reference frame transformation is presented in [10].

As shown in Fig. 2, the reactive power droop characteristic can be modified using the VIm gain $k_{\text{VIm}}$. With a positive value of VIm gain $k_{\text{VIm}}$, the droop characteristic shifts toward the left. The mentioned modification increases the tolerable voltage sag limit by reducing reactive power output when the voltage sag increases. A proper tradeoff between the increase in tolerable voltage sag limit and the decrease in the reactive power output is achieved by selecting an optimal value of $k_{\text{VIm}}$.

The model of the VIm is derived as follows:

$$I_{\text{invd}} = \frac{1}{(R_g + sL_g)} I_{\text{invq}} + \frac{1}{(R_g + sL_g)} (V_{\text{PCC,d}} - V_{\text{gd}})$$ (8)

$$I_{\text{invq}} = -\frac{1}{(R_g + sL_g)} I_{\text{invd}} + \frac{1}{(R_g + sL_g)} (V_{\text{PCC,q}} - V_{\text{gq}}).$$ (9)

The model of the $L$-$C$ filter of the inverter is derived as follows:

$$I_{L,d} = \frac{1}{(R_f + sL_f)} I_{L,q} + \frac{1}{(R_f + sL_f)} (V_{C_d} - V_{\text{PCCd}})$$ (10)

$$I_{L,q} = -\frac{1}{(R_f + sL_f)} I_{L,d} + \frac{1}{(R_f + sL_f)} (V_{C,q} - V_{\text{PCCq}})$$ (11)

$$V_{\text{PCCd}} = \frac{1}{s} V_{\text{PCCq}} + \frac{1}{sC_f} I_{C,d}$$ (12)

$$V_{\text{PCCq}} = -\frac{1}{s} V_{\text{PCCd}} + \frac{1}{sC_f} I_{C,q}$$ (13)

$$I_{C,d} = I_{L,d} - I_{\text{invd}}$$ (14)

$$I_{C,q} = I_{L,q} - I_{\text{invq}}.$$ (15)

The model of the VIm is derived as follows:

$$I_{L,\text{invd}} = \frac{\omega f}{s^2 + \omega f s + \omega_f^2} I_{\text{invd}}$$ (16)

$$I_{L,\text{invq}} = \frac{\omega f}{s^2 + \omega f s + \omega_f^2} I_{\text{invq}}$$ (17)
The main objective here is to find the limiting value of dyamic VIm using the model presented by (1)–(25).

For the mentioned objective, the following steps are followed.

**Step 1**: First, the output-by-input ratio of the system is derived as a function of $k_{\text{VIm}}$. Here, the output is the quadrature-axis inductor current $I_{Lq}$ and the input is the voltage amplitude of the PCC $V_{\text{PCC}}$.

\[
\frac{I_{Lq}}{V_{\text{PCC}}} = f(k_{\text{VIm}}). \tag{26}
\]

It is important to mention that the droop characteristic of the S-VOC, i.e., (4) and (5), is nonlinear. This is why the relation (26) is linearized at the operating point where the tolerable voltage sag is maximum, and the reactive power output of the inverter is also the maximum, i.e.,

\[
V_{\text{voc}} = V_{\text{min}} \tag{27}
\]

\[
Q = Q_{\text{rated}}. \tag{28}
\]

**Step 2**: Next, the values of all the parameters other than $k_{\text{VIm}}$ are put into the relation (26). The S-VOC is intended to maintain effective synchronization. When synchronized, the grid voltages and inverter voltages stay very close to the direct-axis voltages of the S-VOC. Hence, it can be approximated as follows:

\[
V_{\text{voc},d} \approx V_{g,d} \approx V_{C,d} \approx V_z \quad \tag{29}
\]

\[
V_{\text{voc},q} \approx V_{g,q} \approx V_{C,q} \approx 0. \tag{30}
\]

**Step 3**: Finally, the root loci of the characteristic equation from (26) are plotted in Fig. 5 by varying the value of dynamic VIm gain $k_{\text{VIm}}$. The limiting value of $k_{\text{VIm}}$ is found to be 0.22 $\Omega$/A for the given system. Because two of the root loci go to the real part of the phase plane when the value of the $k_{\text{VIm}}$ is greater than 0.22 $\Omega$/A.
It is important to mention that the derived model and the method of analysis presented in this article are not relevant only to finding the boundary value of $K_{VIm}$. The mentioned model and the method can be useful for other important analyses, such as follows.

1) The same procedure and model can be used to derive the limiting conditions of $R_{VO}$, $X_{VO}$, $m$, and $n$ separately if required. For calculating the boundary condition of any parameter of the proposed controller for any given system, the transfer function presented in (26) must be presented in terms of the same variables. The other variables need to be put as constant. Then, using the steps presented in this section, the limiting value of the required parameter can be derived.

2) The change in dynamics of the controller due to the change in the value of any particular parameter can be observed by plotting the loci of the zeros of the transfer function (26).

V. THEORETICAL VALIDATION USING SIMULATION STUDY

A simulation study is presented in this section to exhibit the importance of the proposed voltage stiffness control loop for an existing VOC under a voltage sag. The schematic diagram of the system considered for the simulation studies is presented in Fig. 1.

The values of the power system and VOC parameters are taken from the articles presented in [9], [12] and are given in Table I. The active power reference per phase $P^*$ is set at $P_{rated}$, 350 W. The value of the current scaling factor $k_i$ is 0.2 V/A. The rated reactive power output of the inverter per phase $Q_{rated}$ is 350 Var. As depicted in Fig. 6(a), the inverter reaches the rated reactive power output when the voltage of PCC is lowered to 72.5 V, i.e., at 9.37% voltage sag. Hence, with $k_i = 0.2$ V/A, the maximum tolerable voltage sag is 9.37%. Any higher voltage sag leads to the transition from the grid-forming mode to the current control mode.

Now, the tolerable voltage sag limit can be increased by increasing the value of $k_i$, as shown in Fig. 6(a). However, as depicted in Fig. 6(b), simultaneously, the frequency support capability of the inverter is lowered. Frequency support is one of the main objectives of a grid-forming inverter. As a result, by design, the existing VOCs [9], [12] restrict themselves within 10% tolerable voltage sag to achieve higher frequency support. However, as presented in the following text, it has serious consequences in a weak grid situation.

Without any reactive power support from the grid-forming inverter, the voltage amplitude of the PCC drops by 24.81% when a large load ($2.5 \Omega + 10$ mH)/phase is added to the PCC.

Next, the grid-forming inverter controlled by a VOC without the proposed voltage stiffness control loop is connected to the PCC. As shown in Fig. 7, the current output tends to reach the overcurrent limit. As a result, the current saturation and the antiwindup controller inside the current control loop are activated to restrict the output current under the overcurrent limit. The current output is restricted, but a large oscillation occurs in active and reactive power output due to the loss of effective synchronization.

Now, the proposed adaptive voltage stiffness controller is used with a VIm gain $k_{VIm}$ of 0.07 Ω/A to modify the reactive power droop characteristics, as presented in Fig. 2. With modification in the reactive power droop, the quadrature-axis current is also changed, as shown in Fig. 8. As a result, the output current no longer exceeds the overcurrent limit. Therefore, the inverter stays operating in grid-forming mode and supports the PCC with reactive power, as shown in Fig. 9. The voltage profile of the PCC
is improved (from 24.8% sag to 17.19% sag) by the support of the inverter.

Finally, it is very important to prove that the modification in reactive power droop characteristics by the use of $V_{\text{Im}}$ does not affect the active power droop characteristic. The active power droop response of the inverter without and with the added $V_{\text{Im}}$ is obtained. The frequency of the grid is changed from 60 to 59 Hz in five discrete steps, and the active power output of the inverter is plotted in Fig. 10. The voltage of the PCC is kept at the nominal value. The active power droop response of the inverter without and with the $V_{\text{Im}}$ is nearly the same and closely follow the desired active power droop characteristic.

VI. EXPERIMENTAL RESULTS AND DISCUSSIONS

The functionalities and effectiveness of the proposed $V_{\text{Im}}$-based dynamic voltage stiffness control technique are validated experimentally using insulated-gate bipolar transistor (IGBT) switch-based 15 kVA Semikron inverter modules.

The schematic diagram and the photograph of the experimental setup are illustrated in Figs. 11 and 12, respectively. As depicted in Fig. 11, a constant amplitude and frequency inverter $I_{\text{inv}}$ behind an inductance $L_{g}$ acts as the grid. The frequency and voltage amplitudes of $I_{\text{inv}}$ are controllable. The grid emulator acts as an ideal sink or source throughout the operating range, i.e., 25 A continuous rms current. The three-phase rectifier $\text{Rec}_{2}$, which is connected to the utility grid, energizes the dc-link ($V_{\text{dc}_{\text{p2}}}, V_{\text{dc}_{\text{n2}}}$) of the inverter $I_{\text{inv}}$. The specification of the experimental setup is presented in Table II. An OPAL-RT real-time controller (OP4510) is used to deploy the control strategy.

Fig. 10. Active power droop response of the VOC without and with the proposed voltage stiffness controller.

Fig. 11. Schematic diagram of the experimental setup.

Fig. 12. Photograph of the experimental setup.

A. Dispatchable Operation

At first, the normal dispatchable operation is conducted. The aim is to observe if there is any adverse effect on the normal operation due to the $V_{\text{Im}}$. $V_{\text{Im}}$ gain $k_{\text{Im}} = 0.05 \, \Omega/A$. The three-phase active power reference is initially set to 1500 W. The phase currents and the active power outputs of the inverter are shown in Fig. 13. Initially, each phase injects 500 W of the active power into the grid emulator. Then, the reference is increased to 2400 W. It is observed that the controller successfully tracks the active power reference. The proposed controller has similar first-order active power dynamics, such as an existing VOC [12] with a settling time of approximately 100 ms.

B. Effect of $V_{\text{Im}}$ on Reactive Power Output

The reactive power output of the inverter is observed under two different voltage sags (5% and 25%) with two different values of $V_{\text{Im}}$ gain ($0.05 \, \Omega/A$ and $0.15 \, \Omega/A$). The reactive power outputs of the inverter in the mentioned conditions are shown in Figs. 14 and 13.

The following conclusion can be drawn from the above observations.
TABLE III

| Functionality                          | Droop controller [13], [21]-[23] | Virtual Synchronous Machine Controller [26] | Existing VOC [8], [9] | The Proposed VOC with Voltage Stiffness Control |
|---------------------------------------|----------------------------------|---------------------------------------------|----------------------|-----------------------------------------------|
| Required feedback parameters         | Required phase-based AC parameters as feedback, which are only well-defined in sinusoidal steady state | Required phase-based AC parameters as feedback, which are only well-defined in sinusoidal steady state | Asymptotic stability from an arbitrary initial condition by using only locally available time-domain parameters | Asymptotic stability from an arbitrary initial condition by using only locally available time-domain parameters |
| Time-domain synchronization           | No                               | Yes                                         | Yes                  | Yes                                          |
| Decoupled control over reactive power droop characteristic | Yes | Yes | No | Yes |
| Current control during fault conditions | Yes | Yes | Yes | Yes |
| Dynamic control over voltage stiffness | Yes | Yes | No | Yes |

7) With the increase in VIm gain \(k_{\text{VIm}}\), the voltage stiffness of the inverter increased. As a result, the inverter injects lesser reactive power into the grid under a voltage sag.

2) The difference in reactive power outputs for two different VIm gains is comparatively lesser at 5% voltage sag. The difference in reactive power outputs increases at higher voltage sag (i.e., 25%). The effect of the applied VIm is more prominent at higher voltage sag than at lower voltage sag. It signifies that the voltage stiffness stays lower during lower voltage sags and increases at a much higher rate during higher voltage sags due to the effect of the proposed technique.

3) The peak value and steady-state value are decreased, and the overshoot and settling time are increased with an increase in VIm gain \(k_{\text{VIm}}\).

4) The overshoot and settling time increase with an increase in voltage sag.

C. Effect of VIm on Active Power Droop

Finally, the effect of the proposed method on the active power droop characteristic, which is responsible for frequency support, is examined by creating frequency dips from the grid emulator. The three-phase active power reference is set to 1500 W. The performance of the inverter under two different frequency dips (from 50 to 49.85 Hz and 49.7 Hz) with two different values of VIm gain (0.05 \(\Omega/\text{A}\) and 0.15 \(\Omega/\text{A}\)) is observed. The active power outputs of the inverter in the mentioned conditions are shown in Figs. 16 and 17. The responses for two different virtual gains are nearly indistinguishable. The active power dynamics remain first order. The steady-state value and the settling time remain nearly the same for the different values of VIm gains but change with the change in the value of frequency dip. The results indicate that the effect of the added VIm is very little on the frequency droop characteristics and, hence, the voltage stiffness without leaving any noticeable effect on the frequency support performance.

The improvement in terms of functionalities of the proposed VOC with voltage stiffness control loop over the existing grid-forming controllers is summarized in Table III.

VII. Conclusion

Voltage stiffness control is a crucial functionality for any grid-forming inverter, especially under weak grid situations. However, the existing VOC, the latest and most advanced grid-forming controller, does not have the mentioned ability.

In this article, we primarily focused on integrating a dynamic voltage stiffness control loop inside a VO-based grid-forming controller. To achieve the mentioned goal, the concept of the VIm method, which has a phasor-based implementation, was incorporated into a time-domain VOC. A detailed and systematic design procedure with analytical reasoning was presented. This article had also presented a rigorous approach for the stability analysis for VO-based grid-forming controllers. The range of the control parameters can be obtained using the mentioned
stability analysis. The functionalities of the proposed controller were validated in detail using simulation studies and hardware experiments. Along with the primary objective, the proposed concept of integrating the VIm method into a VOC had further applications, such as improving reactive power sharing among parallelly connected inverters. The proposed design and analytical approaches were general and valid for other applications, such as the one mentioned above.

**REFERENCE**

[1] L. A. B. Torres, J. P. Hespanha, and J. Moehlis, “Power supply synchronization without communication,” in *Proc. IEEE Power Energy Soc. Gen. Meeting*, 2012, pp. 1–6.

[2] L. A. B. Torres, J. P. Hespanha, and J. Moehlis, “Synchronization of identical oscillators coupled through a symmetric network with dynamics: A constructive approach with applications to parallel operation of inverters,” *IEEE Trans. Automat. Control*, vol. 60, no. 12, pp. 3226–3241, Dec. 2015.

[3] B. B. Johnson, M. Sinha, N. G. Ainsworth, F. Dörfler, and S. V. Dhople, “Synthesizing virtual oscillators to control islanded inverters,” *IEEE Trans. Power Electron.*, vol. 31, no. 8, pp. 6002–6015, Aug. 2016.

[4] M. Sinha, F. Dörfler, B. B. Johnson, and S. V. Dhople, “Uncovering droop control laws embedded within the nonlinear dynamics of Van der Pol oscillators,” *IEEE Trans. Control Netw. Syst.*, vol. 4, no. 2, pp. 347–358, Jun. 2017.

[5] Z. Shi, J. Li, H. I. Nurdin, and J. E. Fletcher, “Comparison of virtual oscillator and droop controlled islanded three-phase microgrids,” *IEEE Trans. Energy Convers.*, vol. 34, no. 4, pp. 1769–1780, Dec. 2019.

[6] H. Yu, M. A. Awal, H. Tu, I. Husain, and S. Lakic, “Comparative transient stability assessment of droop and dispatchable virtual oscillator controlled grid-connected inverters,” *IEEE Trans. Power Electron.*, vol. 36, no. 2, pp. 2119–2130, Feb. 2021.

[7] V. Gurugubelli, A. Ghosh, A. K. Panda, and S. Rudra, “Implementation and comparison of droop control, virtual synchronous machine, and virtual oscillator control for parallel inverters in standalone microgrid,” *Int. Trans. Elect. Energy Syst.*, vol. 31, no. 5, May 2021, Art. no.e12859.

[8] O. Ajala, M. Lu, B. Johnson, S. V. Dhople, and A. Domínguez-García, “Model reduction for inverters with current limiting and dispatchable virtual oscillator control,” *IEEE Trans. Energy Convers.*, vol. 37, no. 4, pp. 2250–2259, Dec. 2022.

[9] M. Lu, R. Mallik, B. Johnson, and S. Dhople, “Dispatchable virtual-oscillator-controlled inverters with current-limiting and MPPT capabilities,” in *Proc. IEEE Energy Convers. Congr. Expo.*, 2021, pp. 3136–3133.

[10] R. Ghosh, N. R. Tummuru, and B. S. Rajpurohit, “A new virtual oscillator-based grid-forming controller with decoupled control over individual phases and improved performance of unbalanced fault ride-through,” *IEEE Trans. Ind. Electron.*, vol. 70, no. 12, pp. 12465–12474, Dec. 2023.

[11] A. Tuckey and S. Round, “Grid-forming inverters for grid-connected microgrids: Developing ‘good citizens’ to ensure the continued flow of stable, reliable power,” *IEEE Electr. Mag.*, vol. 10, no. 1, pp. 39–51, Mar. 2022.

[12] M. Lu, S. Dutta, V. Purba, S. Dhople, and B. Johnson, “A grid-compatible virtual oscillator controller: Analysis and design,” in *Proc. IEEE Energy Convers. Congr. Expo.*, 2019, pp. 2643–2649.

[13] A. S. Vijay, N. Parth, S. Doolla, and M. C. Chandorkar, “An adaptive virtual impedance control for improving power sharing among inverters in islanded AC microgrids,” *IEEE Trans. Smart Grid*, vol. 12, no. 4, pp. 2991–3003, Jul. 2021.

[14] M. T. Hagh and T. Khalili, “A review of fault ride through of PV and wind renewable energies in grid codes,” *Int. J. Energy Res.*, vol. 43, pp. 1342–1356, Mar. 2019.

[15] M. A. Awal and I. Husain, “Unified virtual oscillator control for grid-forming and grid-following converters,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 9, no. 4, pp. 4573–4586, Aug. 2021.

[16] X. Wang, Y. W. Li, F. Blaabjerg, and P. C. Loh, “Virtual-impedance-based control for voltage-source and current-source converters,” *IEEE Trans. Power Electron.*, vol. 30, no. 12, pp. 7019–7037, Dec. 2015.

[17] M. G. Taul, X. Wang, P. Davari, and F. Blaabjerg, “Current limiting control with enhanced dynamics of grid-forming converters during fault conditions,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1062–1073, Jun. 2020.

[18] A. D. Paquette and D. M. Divan, “Virtual impedance current limiting for inverters in microgrids with synchronous generators,” *IEEE Trans. Ind. Appl.*, vol. 51, no. 2, pp. 1630–1638, Mar/Apr. 2015.