A Virtual Synchronous Control for Voltage-Source Converters Utilizing Dynamics of DC-Link Capacitor to Realize Self-Synchronization

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Abstract: Voltage-source converters (VSCs) are widely used in renewable energy sources as the gridiron interface, e.g., wind turbine generators and photovoltaic. These VSCs ascendancy the dc-link capacitor voltage and the reactive power production to track the reference values, which generally apply phase-locked loop (PLL) for grid synchronization. However, the dynamic performance of the conventional PLL can be deteriorated when the VSC is integrated into weak grids, which may even cause instability of the VSC. In this paper, a virtual synchronous control (ViSynC) is proposed for VSCs, which utilizes the dynamics of the dc-link capacitor to realize self-synchronization. Grid synchronization mechanism of the ViSynC-based VSC is mainly analyzed in this paper. The sync-based VSC can provide inertial responses to the grid, and has the advantage that it can operate normally under weak grid conditions without any modification of the grid synchronization unit. Furthermore, virtual impedance and Q–V droop control can be easily applied in the control structure of the ViSynC. Simulations based on MATLAB and hardware-in-the-loop real-time simulations based on RT-LAB verify the effectiveness of the proposed Vsync

Index Terms*—*DC-link voltage control, grid synchronization, inertia emulation, virtual synchronous control (ViSynC), voltage-source converter (VSC), weak grids.

I. INTRODUCTION

The new power grid is qualified by the high insight of renewable energy sources such as wind turbine generators and photovoltaic, which are as a rule connected to the network via voltage source converters (VSCs) [1], [2]. The VSC can be affected as a controlled voltage source or current source whose phase and inside control strategies determine amplitude. These control strategies command the output characteristics of the VSC confronted to the power grid. Old control methods extract the maximum active power to the network so that the VSCs act as fi power sources and have fixed responses to frequency oscillations from the power grid [3], [4]. Since, it will result in the diminishing of the whole inertia of the power grid and weakens the frequency rule capability, which cannot fulfill the new grid code [5]. To take with this problem, frequency regulation schemes such as primary frequency control and inactivity emulation were acquainted in the power of VSCs [6]–[8].

There are mainly two methods to implement frequency regulation strategies. One is to modify the active power reference by introducing the feedbacks of grid frequency deviation signal (f) and the grid frequency derivative signal (d f /DT) in the control of VOCs [9]. This method is generally used for VSCs with vector control and a phase-locked loop (PLL). However, the maximum applied PLL, which is conceived to be the basis for grid synchronicity of the VSC, may cause instability to the VSC system with different parameters, especially when the VSC is merged to weak grids characterized by low short circuit ratio (SCR) [10], [11]. The reactivity and tracking performance of the ceremonious synchronous reference frame (SRF) PLL can degenerate in debile grids [12], [13], which may even result in the imbalance of dc-link voltage control [14].

To address this problem, the control construction of the old SRF-PLL should be modified. In [15], an impedance-conditioning term is brought in in the PLL so that the PLL-based VSC can control under weak grid conditions. Another method to achieve frequency regulation is practical synchronous machine (VSM) control [or virtual synchronous generator (SG)], which mimics frequency ordinance characteristics of SGs in order that the VSC can provide inertial reactions for the grid [16]–[18], and it can be given to wind turbine generators as well [19]. The PLL can be absented by competing for the SG's swing equation in the control of VSCs to realize grid synchronization [20], [21]. When classified by the control objectives, there are two main types of VSCs. One type of VSC assures the alive and reactive power outputs (abridged to PQ-type VSC in this paper) [18], which works at the condition that the dc-link voltage is fixed or is well controlled.

This PQ-type VSC is widely given as the grid port of energy storage systems, and can also be applied in one place of the VSC-HVDC transmission system to check the active power flow [22]. Different type of VSC controls the dc-link voltage and the reactive power output (abridged to DCVQ-type VSC in this paper) [23]. This DCVQ-type VSC is chiefly designed to control the dc-link voltage, and its active power output is ascertained by the dynamic power flow of the power network. For example in a back-to-back system, there is usually a PQ-type VSC on one side to assure the active power flow, and a DCVQ-type VSC on the other hand to control the dc-link voltage. The dc-link voltage is determined within the allowable range by the DCVQ-type VSC so that the two VSCs can operate pulse width modulation (PWM).

The DCVQ-type VSC is wide applied in renewable energy sources, e.g., the grid-side converters of wind turbine generators and photovoltaic [24]–[28]. Furthermore, it is also applied in one of the stations of VSC-HVDC systems and in dc micro grids for determining the dc voltage. The PQ-type VSC and the DCVQ-type VSCs have different control objectives and are contrived for different application scenarists mentioned above. These two types of VSCs cannot interchange each other in particular application scenarios. Up to now, almost VSM-based control strategies are contrived for PQ-type VSCs [18], [20], [31], and these control strategies cannot be easy extended to be used in DCVQ-type VSCs. There is also control connives that designed for the DCVQ-type VSC to come in the frequency control of power grids [22], [27], [33]. These control strategies broadly employ the dynamics of the dc-link capacitor to mime the dynamics of the SG's rotor so that convertible inertial reactions can be allowed. Whereas, PLL is still asked

in these control schemes to actualise grid synchrony. Xiong et al. [32] analyzed the DCVQ-type VSC from a new position of "Static Synchronous Generator Model," which enquired the VSC's dynamics and stability by bearing on to the analytical methods of SGs. The DCVQ-type VSC was attested to have similar dynamics to SGs, but the grid synchronization unit was not concentred in [32]. In [33], the dc-link part of a grid-interfaced VSC is demonstrated to be tantamount to the rotor dynamics of SGs, and the dc-link voltage isincorporated to obtain the virtual rotor angle so that the VSC can emulate the dynamic behaviors of SGs. However, the control scheme in [33] requires a resistor in series with the dc-link capacitor to follow the winding damper effect, and the VSC's dynamic behavior is determined by the capacitance and the resistance of the dc-link part. In this paper, a virtual synchronous control (ViSynC) is proposed for the DCVQ-type VSC, which utilizes the dynamics of the dc-link capacitor to realize self-synchronization. When being integrated into weak grids, the DCVQ-type VSC with ViSynC can operate normally without any modification of the grid synchronization unit. Grid synchronization mechanism of ViSynC-based VSC will be mainly analyzed in this paper.

II. SYNCHRONOUS ascertain FOR DCVQ-TYPE VSC

This section will give the elaborate control scheme and implementation of the advised ViSynC for DCVQ-type VSCs. A three-phase VSC with an LCL filter is believed as the grid port in this paper, which changes the active power from a power source into the three-phase ac system, as shown in Fig. 1. CDC is the dc-link capacitor. L F is the converter-side filter inductor. CF is the filtrate capacitor. Lg is the control grid-side inductor of the LCL filter. Ll comprises of the leakage inductor of the isolation transformer and the inductor of the line. RL is the equivalent series resistor. The voltage of the dc-link capacitor is dominated by the VSC so that PWM can be engaged. The control construction of the ViSynC is given in Fig. 1, and the effectuations are exempted in the following.

A DC-Link Voltage accountant

The dc-link voltage of the ViSynC, as described in Fig. 1, controls the dc-link voltage to track the base value. It also works as the grid synchronization part of the VSC, which utilizes the dynamics of the dc-link capacitor to actualize self-synchronization.

$$\omega^* = \omega_g + \frac{s+K_T}{K_J s + K_D}\left[(V_{\mathrm{DC}})^2 - (V_{\mathrm{DC}}^{\mathrm{ref}})^2\right]$$

$$(V_{\mathrm{DC}})^2 - (V_{\mathrm{DC}}^{\mathrm{ref}})^2 = \frac{(1-m)K_D}{K_T}(\omega^* - \omega_0).$$

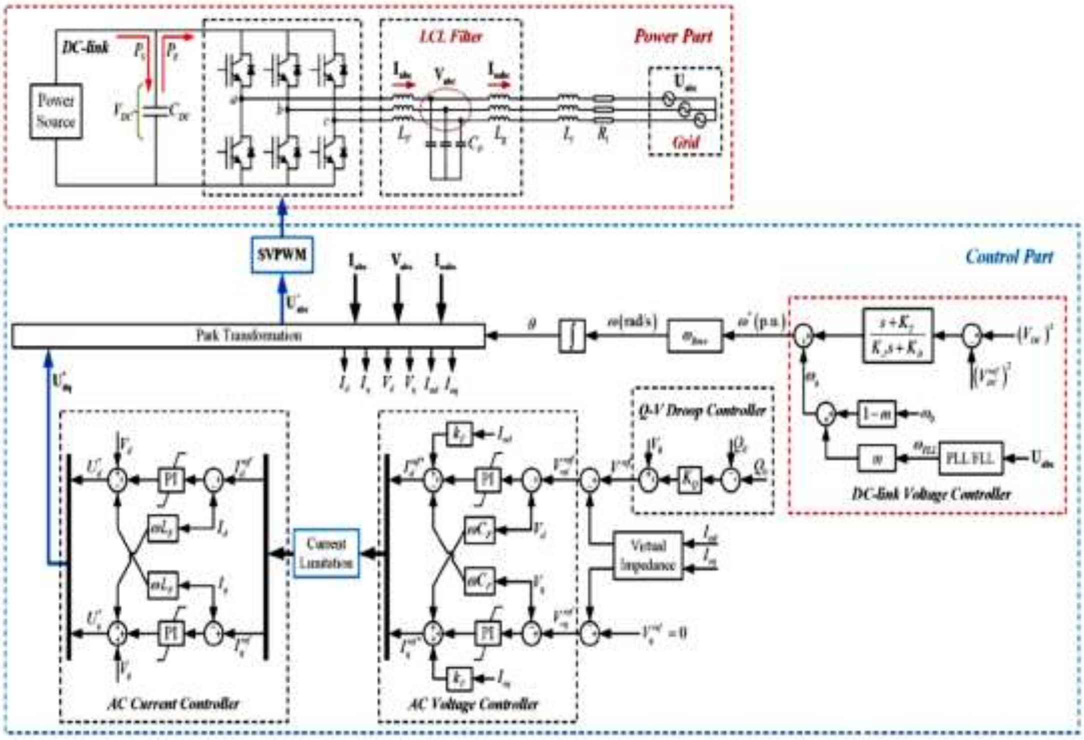

Fig. 1.0. Diagram of the ViSynC-based VSC system.

The basic control strategy is where ω∗(p.u.) is the angular frequency of the rotating dq-axis for Park transformation and it can also be regarded as the VSC's frequency output, ωg(p.u.) is the frequency setting value, VDC(p.u.) is the dc-link voltage, V ref DC(p.u.) is the reference value, K D is the damping coefficient of the ViSynC, KJ is the inertia emulation coefficient, and KT is the dc-link voltage tracking coefficient. Substituting s = 0 into (1) yields the relationship between ω∗ and VDC in steady state, which is

$$\omega^* = \omega_g + \frac{K_T}{K_D}\left[(V_{\mathrm{DC}})^2 - (V_{\mathrm{DC}}^{\mathrm{ref}})^2\right].$$

The frequency setting value ωg can be obtained by

$$\omega_g = m \times \omega_{\mathrm{PLL}} + (1-m) \times \omega_0$$

where ωPLL is obtained by a PLL (or frequency-locked loop (FLL) [35], [36]) to detect the steady-state grid frequency, ω0 = 1.0 p.u. is the nominal frequency value, and m is a weighting coefficient. In steady state, both ω∗ and ωPLL are equal to the grid frequency, i.e., ω∗ = ωPLL.

It can be seen from (4) that the value of m influences the dc-link voltage deviation under grid frequency deviation. With m = 1, VDC = V ref DC holds in steady state, even under grid frequency deviations. That is, the control strategy in (1) provides the VSC with dc-link voltage tracking capability. Also, sometimes small dc-link voltage deviations within admissible range is acceptable. With m = 1, (4) is similar to the frequency control proposed in [37] and [38], which sets a linear relationship between dc-link voltage and frequency to realize communication-free inertia and frequency control. In this case, the dc-link voltage will deviate from the reference value V ref DC under grid frequency deviations. Setting m closer to 1 can reduce the dc-link voltage deviation and prevent the dc-link voltage from exceeding admissible range, which will be further verified by the simulation results in Section V. It should be noted that the PLL/FLL used in Fig. 1 is only for detecting the steady-state value of grid frequency, not to realize grid synchronization of the VSC. Theoretically the ViSynC works without the PLL/FLL (i.e., m = 0), but in this case, K D and KT should be tuned carefully to ensure that the dc-link voltage deviation is acceptable under grid frequency deviations. Also, many other ways can be used to obtain the steady-state value of grid frequency. Without loss of generality, an SRF-PLL is used in this paper to detect the grid frequency.

II.LITERATURE REVIEW

Qing-Chang Zhong (M'04–SM'04) received the Ph.D. degree in control and power engineering (awarded the Best Doctoral Thesis Prize) from Imperial College London, London, U.K., in 2004. He is currently the Chair Professor in control and systems engineering in the Department of Automatic Control and Systems Engineering, The University of Sheffield, Sheffield, U.K. From 2012 to 2013, he spent a six-month sabbatical at the Cymer Center for Control Systems and Dynamics, University of California

A synchro converter is an inverter that mimics synchronous generators, which offers a mechanism for power systems to control grid-connected renewable energy and facilitates smart grid integration. Similar to other grid-connected inverters, it needs a dedicated synchronization unit, e.g., a phase-locked loop (PLL), to provide the phase, frequency, and amplitude of the grid voltage as references. In this paper, a radical step is taken to improve the synchro converter as a self-synchronized synchro converter by removing the dedicated synchronization unit. It can automatically synchronize itself with the grid before connection and track the grid frequency after connection. This considerably improves the performance, reduces the complexity, and computational burden of the controller.

More renewable energy sources are being connected to power systems, often via dc/ac converters (also called inverters). The most important and basic requirement for such applications is to keep inverters synchronized with the grid before and after being connected to the grid so that 1) an inverter can be connected to the grid and 2) the inverter can feed the right amount of power to the grid even when the grid voltage changes its frequency, phase, and amplitude [1]–[8]. It has been a norm [9] to adopt a synchronization unit, e.g. a phase-locked loop (PLL) and its variants [4], [10]–[15], to make sure that the inverter is synchronized with the grid. This practically adds an outer-loop controller (the synchronization unit) to the inverter controller

Title: Modeling of a virtual synchronous machine-based grid-interface converter for renewable energy systems integration.

The common, and with some exceptions, the only method to interconnect high power renewable energy sources and energy storage systems to the power system has been using power electronics converters that operate as current sources to the grid, for the purpose of achieving maximum primary-source power tracking. When grid is not available, such sources are not allowed to continue operating and are shut-down after anti-islanded algorithms recognize the loss of the grid. Although existing standards and requirements still limit grid-interface converters to regulate voltage in the grid, this functionality will most probably be the dominant mode of their operation in the future grid; hence the growing trend in industry and academia to concentrate research towards control of the grid-interface converters that resemble behavior of the classic synchronous generators. This paper addresses modeling of the virtual synchronous machine-based grid-interface converters for renewable energy systems integration. Being completely equivalent to the synchronous generator model, an average model of the grid-interface converter features an inherent frequency-locked loop, in which the virtual rotor angle is obtained by integrating dc-link voltage.

III.PROPOSED PV-STORAGE SYSTEM ARCHITECTURE

Simulations based on MATLAB are carried out to investigate the time-domain responses of the ViSynC-based VSC and the influences of the control parameters. The VSC system depicted in Fig. 1 is considered. The parameters of the system can be found in Appendix A. The ac grid in Fig. 1 is modeled as a three-phase voltage source whose voltage amplitude and frequency are fixed at 1 p.u. and 50 Hz, i.e., an “infinite bus.” Assuming that the active power input of the power source (i.e., PS) steps from 0.3 to 0.6 p.u. at t = 2 s, the responses of the ViSynC-based VSC with different values of K D are given in Fig. 10. Some oscillating behavior occurs with K D = 150, but it is well damped with K D = 750, which is consistent with the small-signal analysis results obtained from Figs. 8(a) and 9(a). The VSC has desired dynamic performance especially with K D = 750, as the active power PE , reactive power QE , dc-link voltage VDC, and frequency output f ∗ all track the reference values very well and have quick responses. Under the same disturbance, the responses of the ViSynC-based VSC with different values of KJ are shown in Fig. 11. With the increase of KJ from 2.5 to 50, the VSC has slower responses as the equivalent inertia increases, consistent with the small-signal analysis results obtained from Fig. 8(b) that the bandwidth is reduced. With the increase of KJ, the dynamics of the system can be deteriorated.

IV.RESULTS AND DISCUSSION

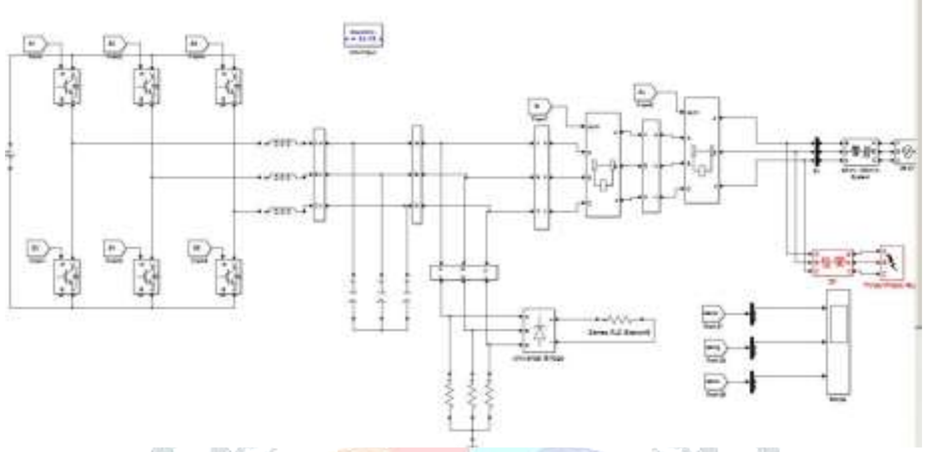

Fig:4.1.Proposed System

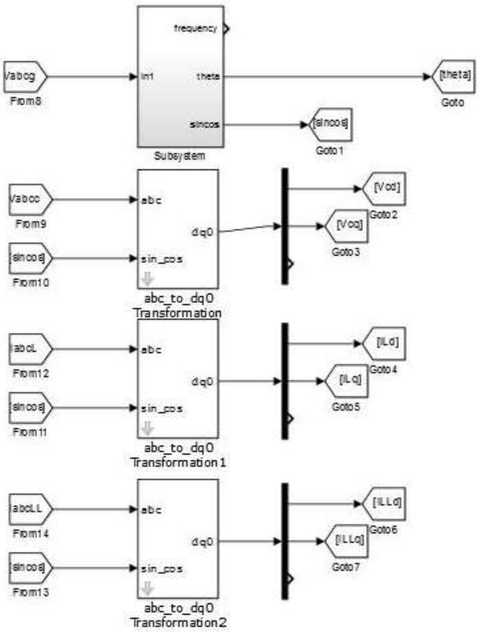

Fig:4.2.d-q Transformation

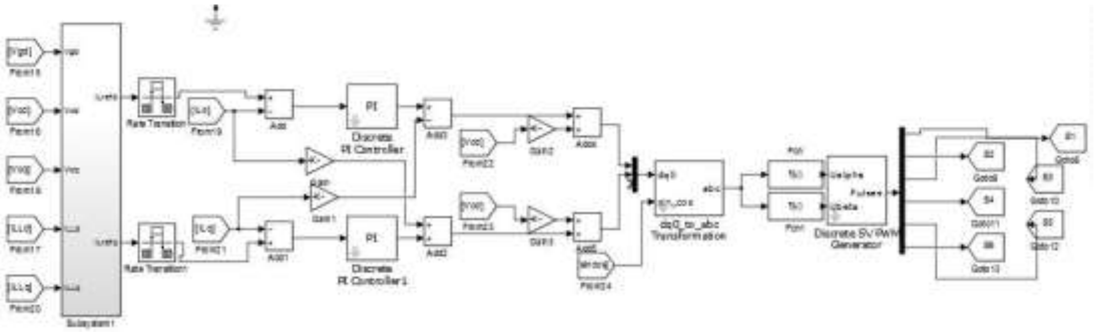

Fig:4.3.Subsystem System

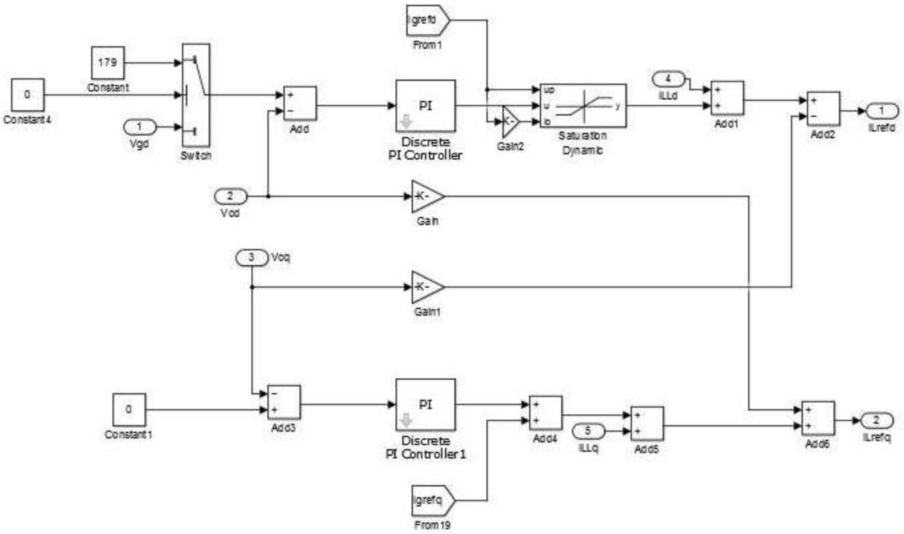

Fig:4.4.PID Controller

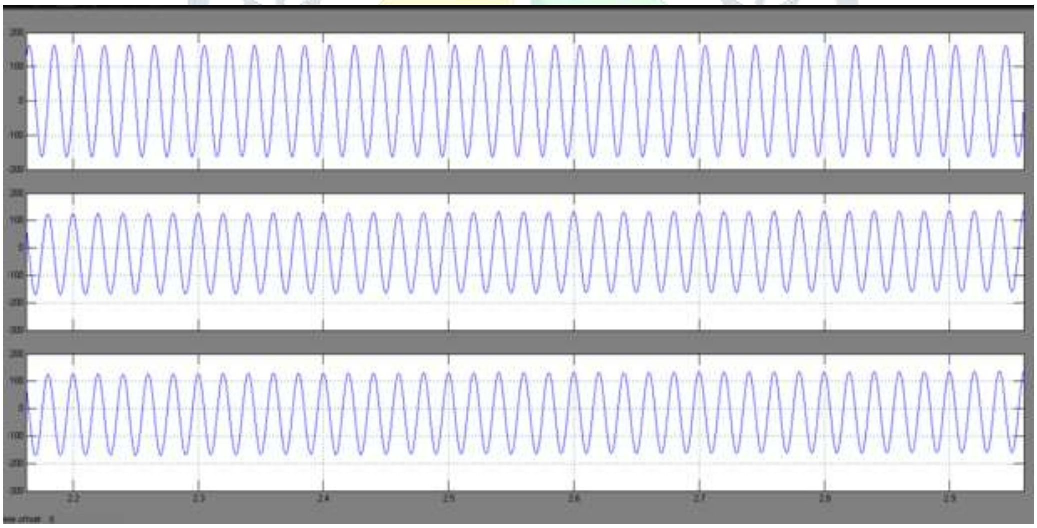

Fig.4.5. output voltage, grid current and load current of proposed system

V.CONCLUSION

In this paper, a ViSynC is proposed for the DCVQ-type VSC, which can utilize the dynamics of dc-link capacitor to realize self-synchronization. The implementation, grid synchronization mechanism, inertia emulation, and stability analysis of the ViSynC-based VSC are described in detail. The ViSynC-based VSC presents desired dynamic performance when integrated to weak grids. Inertia emulation can be configured conveniently in the ViSynC. Simulation and HIL results are provided to test the dynamic performance of the ViSynC under disturbances. The proposed ViSynC has the potential to be applied in photo voltaics, wind turbines, VSC-HVdc systems, and so on, as these application scenarios commonly need DCVQ-type VSCs to regulate the dc-link voltage.

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