VSG-VFOC Pre-synchronization Control for Graceful Mode Transition of Inverter-based AC Microgrid

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***Abstract*—This paper presents a novel virtual synchronous generator (VSG) based multi-loop control solution with the virtual flux oriented control (VFOC) aiming to efficiently manage the microgrids under dynamics. The pre-synchronization control aligned to the outer loop of such VSG-VFOC solution is investigated to ensure smooth microgrid operational transition between island to grid-connected modes. Simulation results in comparison with voltage oriented control (VOC) clearly validate the effectiveness of the proposed solution in timely current response and static error free tracking control of output voltage.**

Index Terms—Virtual synchronous generator (VSG); Virtual flux oriented control (VFOC); Grid-connected process.

I. INTRODUCTION

An increasing number of inverter-based renewable distributed sources (e.g. photovoltaic, fuel cell and micro wind turbines) are currently integrated in medium/low voltage microgrids. The power generation from these distributed generators (DGs) is intermittent and stochastic in nature, which bring about direct adverse impacts to network operation, e.g. voltage oscillation, altered transient stability and protection degradation. As these renewable DGs cannot introduce any system inertia, the energy system stability can degrade due to disturbances or sudden changes from generation or demand.

In recent years, in addition to the conventional inverter control solutions for microgrids, e.g. constant power control (PQ control), constant Voltage/frequency (V/f) control and droop control [1-3], the virtual synchronous generator (VSG) [4] based control is exploited to enable the renewable sources to exhibit the same exterior characteristics as a synchronous generator. However, available VSG solutions are mostly designed based on the voltage oriented control (VOC) [5], thus the phase angle detection of the bus voltage fundamental component can be affected due to harmonic interferences. Further effort has adopted the virtual flux oriented control (VFOC) in VSG without considering the static errors and phase variation, which results in inaccurate vector orientation process, and even system oscillation, in the presence of high DG penetration. In particular, such adversary impacts need to be minimized in grid-connected micro grid, and an efficient pre-synchronization control approach is required to ensure identical voltage and frequency between the microgrid and grid before the transition from island mode to grid-connected mode. This paper proposes a pre-synchronization control in VSG-based multi-loop control structure to provide a graceful transition in frequency regulation under microgrid dynamics with timely current response and static error-free voltage tracking. The simulation result confirms that the solution can reduce the harmonic interferences and system oscillation as well as improve the dynamic response and power quality than conventional VSG solutions.

II. CONTROL STRUCTURE

Fig. 1 illustrates the multi-loop (outer-loop and the U/I close-loop) VSG control solution to increase the inertia and damping properties of the microgrid. The VFOC-based pre-synchronization control is highlighted.

In island microgrid, DGs based on VSG control can be considered as voltage sources participating in the regulation of frequency and voltage, which often inevitably deviate from grid frequency and voltage. Thus, the microgrid mode switch (from island to grid-connected mode) without pre-synchronization can result in current impulse at the point of common coupling (PCC), and hence unexpected accidents, e.g. equipment damage or grid failure. The feedback and integral of frequency (including the compensations) are used to identify the operating point under load changes or synchronization process in the multi-loop VSG control, which requires accurate control parameters to avoid accumulated errors. To implement the grid voltage phase tracking in pre-synchronization process, VFOC is extended from VOC to minimize the adverse impact of harmonic disturbance on voltage fundamental component detection and guarantee the accuracy of vector orientation process in the presence of harmonic interferences [6].

Based on the current closed-loop control structure, Fig.2 (a) shows the relative vector relationship when VFOC is adopted in the power decoupling control by making the flux vector overlap with d-axis. Fig.2 (b) illustrates the phase tracking process between U and Ug when this vector orientation method is adopted in the pre-synchronization process. Here, two compensations, as given in (1), are added in the VSG outer loop to make U quickly approach to Ug (also shown in Fig. 1).

$$\begin{cases} \omega_p = -(K_{pp}U_{pd} + \int K_{pi}U_{pd}dt) \\ E_p = K_p(U_g - U) \end{cases} \tag{1}$$

VFOC Improvement: The VFOC for pre-synchronization control is further improved in this work as follows: considering the available DC components and initial integration error, existing VFOC methods generally replaces the integrator $G_1(s) = \frac{1}{s}$ with a low-pass filter

(LPF), e.g. $G_2(s)=\dfrac{1}{s+\omega_c}$ to eliminate the integral operation and avoid the orientation errors. For a simple DC signal, $G_2(s)$ can avoid the integrate saturation but not the static error, this effectively break the orthogonality between $\boldsymbol{\psi}$ and $\boldsymbol{U}$, and hence introduces additional complexity in phase tracking process. To this end, this work adopts an improved virtual flux observation method as (2).

$$
\begin{aligned}
G_3(s) &= \frac{\psi(s)}{U(s)} = G_{BPF}(s)*G_c(s) \\
&= \frac{K_B s}{s^2+\frac{\omega_B}{Q_B}s+\omega_B^2}*\frac{1+\tau s}{1+\lambda\tau s}(\lambda>1)
\end{aligned}
\tag{2}
$$

where $G_{BPF}(s)$ is the transfer function of a band-pass filter to ensure the base wave's sole passing and $G_c(s)$ presents a lag compensation to maintain the orthogonality between $\boldsymbol{\psi}$ and $\boldsymbol{U}$.

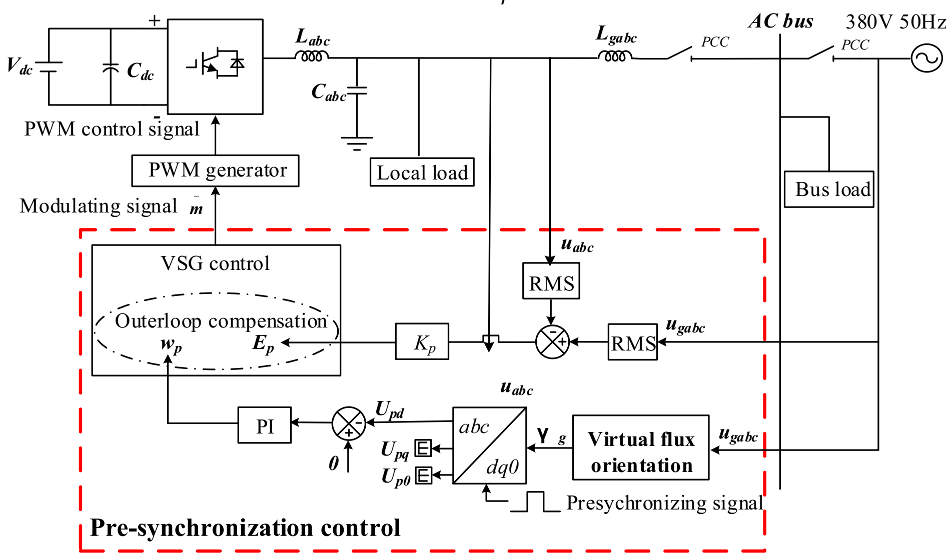


Figure 1. Components of proposed VSG based control

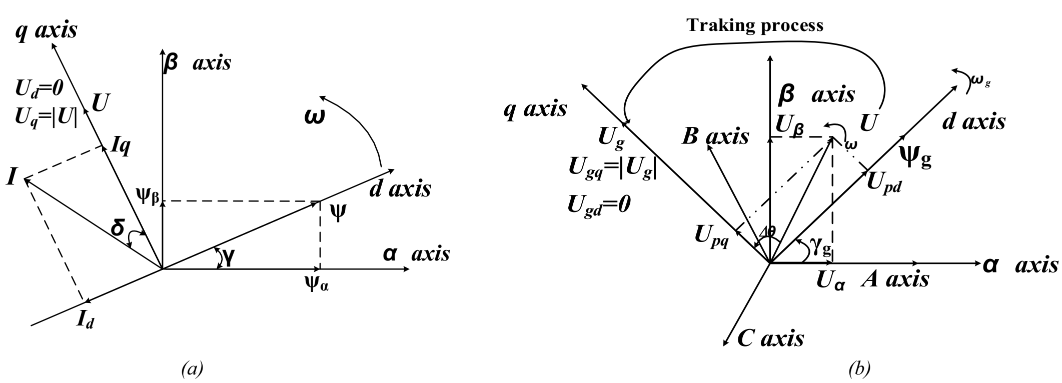


Figure 2. Vector diagram in VFOC scheme

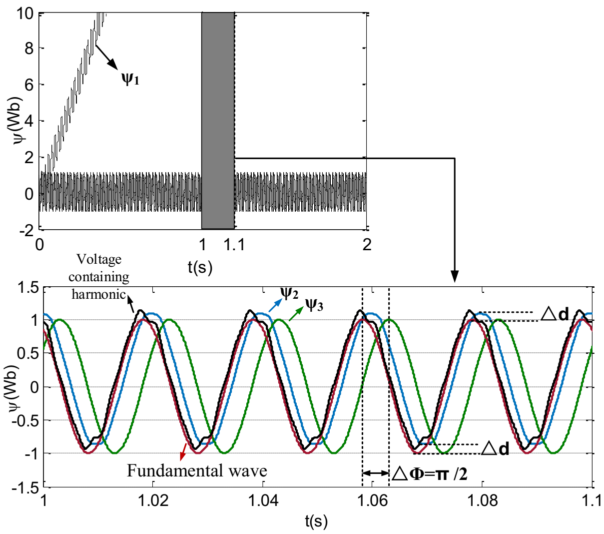
(a) Conventional VFOC in power decoupling control; (b) VFOC in pre-synchronization control process.

Fig.3 presents the status of the output flux vector with the comparison of fundamental waveform when a unit sinusoidal signal with Total Harmonic Distortion (THD) =5.5% (comprising of 5^{th} and 7^{th} harmonics) and 10% DC component are made available to $G_1(s)$, $G_2(s)$, $G_3(s)$ (corresponding to the output of $\boldsymbol{\psi_1}$, $\boldsymbol{\psi_2}$, $\boldsymbol{\psi_3}$), respectively. It is shown in Fig. 3(a) that, due to the existing DC component, $\boldsymbol{\psi_1}$ is significant in integral saturation and cannot reach the periodic steady state. During the time period of 1.0~1.1 s ($\boldsymbol{\psi_2}$ and $\boldsymbol{\psi_3}$ have completed the transient process), a reduced static error Δd with $\boldsymbol{\psi_2}$ and the lag angle of less than $\frac{\pi}{2}$ can be observed. In contrast, $\boldsymbol{\psi_3}$ can eliminate the static error and well maintain the orthogonality with the fundamental waveform.

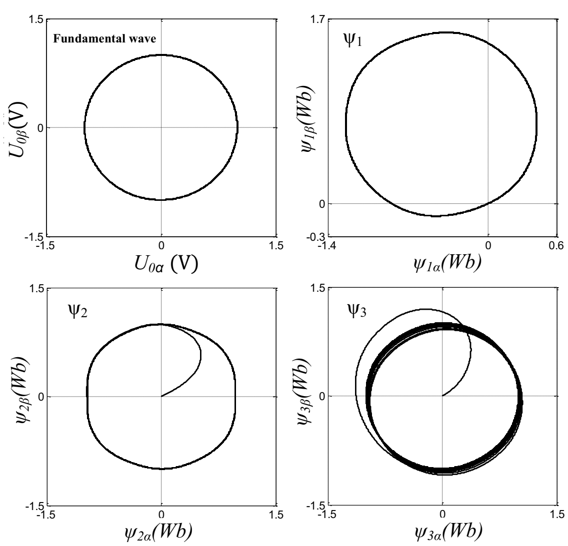
More obvious differences can be observed after a Clarke transformation, as shown in Fig.3 (b). $\boldsymbol{\psi_1}$ deviates from the central point significantly and the static error always exists in the movements of $\boldsymbol{\psi_2}$, whereas $\boldsymbol{\psi_3}$ can finally guarantee the accuracy of virtual flux. Thus, the voltage of d-axis can be well controlled at 0 through an orientation based on $\boldsymbol{\psi_3}$, and hence the improvement of phase tracking process is validated.

III. Numerical Result

The proposed SVG-VFOC pre-synchronization control solution is evaluated through a set of simulation experiments. The circuit element and control parameters are derived based on small-signal analysis [7] and presented in Table 1.



(a)



(b)

Figure 3. Comparison of three virtual flux observation methods
(a) Virtual flux and the voltage waveform.
(b) Virtual flux linkage trajectory after Clarke transformation.

Fig.4 presents the control performance result of proposed VSG-VFOC solution against the existing VOC-based VSG solution in the transition of operational modes. The simulation scenario is described as follows: there is a constant bus load of 70 kW, initial frequency performance shows the droop properties in VSG control scheme. To guarantee the synchronicity between the two sides before the synchronization operation, the pre-synchronization control (based on both VOC and proposed VFOC) with a fast-track process is carried out at 0.3 s, followed by the close of circuit breaker at PCC at 1.5 s to switch the operational of microgrid from island mode to grid-connected mode.

TABLE I
CIRCUIT ELEMENTS AND CONTROL PARAMETERS

Component	Symbol	Parameter	Value
Circuit elements and controller parameters	L_{abc}	Inductance of the inverter output terminal	100 μH
	C_{abc}	Capacitance	330 μF
	L_{gabc}	Inductance of the bus side	8 mH
	$K_{pp}=1, K_{pi}=50$		
	$K_p=5\times10^{-2}$		

Fig.4 (a) and (b) demonstrates that VOC solution results in a longer transition process in mode switching with higher THD. Fig.4 (c) and (d) presents the details of voltage difference between VSG and grid as well as the voltage tracking process as the pre-synchronization is carried out at 0.3 s. Upon the receipt of pre-synchronization signal, the inverter adjusts its output to track the grid voltage (≤5% is generally acceptable). During such process, frequency oscillation can happen in microgrid until the steady state is reached. It can be observed that it takes about 0.2 s (0.3 s ~0.5 s) to complete the pre-synchronization process, and afterwards, power can be exchanged between the microgrid and the grid. In summary, the performance results in terms of bus frequency, bus voltage THD and DG output power clearly confirm that the pre-synchronization control outperforms the existing VOC-based solution in providing a graceful microgrid mode transition with significantly improved system stability and power quality.

IV. Conclusion

This paper presents a novel pre-synchronization control solution through adopting virtual flux oriented control in a multi-loop VSG control structure to provide graceful transitions with improved system stability and power quality under microgrid dynamics. VFOC can guarantee accurate vector orientation process in the presence of harmonic interferences and the synchronous seamless switch shortens the transient process in mode transition. The simulation results confirm the effectiveness on the proposed VSG-VFOC pre-synchronization control solution in managing renewable DGs as plug-and-play components in microgrid under dynamics.

Acknowledgement

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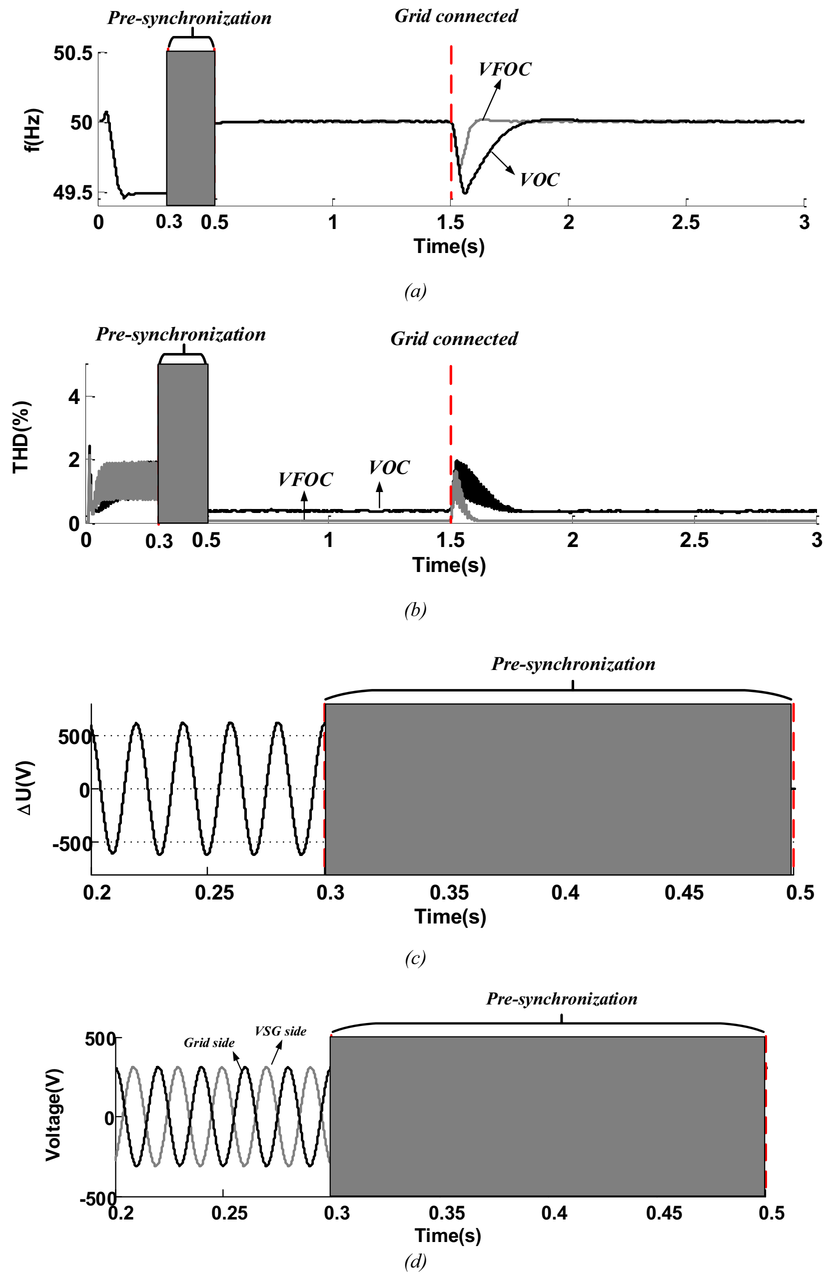

Figure 4. Pre-synchronization and grid-connected process (a) Frequency waveform of ac bus; (b) THD of the bus voltage; (c) Voltage difference between the two sides in VFOC; and (d) Voltage tracking process in VFOC