12-phase virtual synchronous generator

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Abstract

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Abstract—This paper presents a novel 12-phase virtual synchronous generator (VSG). The proposed 12-phase VSG can be used as an AC/DC or DC/AC converter in a multi-energy power system mainly composed of a 12-phase generator to improve the stability of the grid system. Compared with traditional passive converters, the proposed 12-phase VSG has higher output voltage and power, lower harmonic distortion, and improved power quality, making it a more suitable candidate for rectifier applications. The design and control strategy of the 12-phase VSG rectifier is elaborated in detail, including the phase shifting control method and the modulation strategy for the output voltages. The main contributions of this work include the successful design and implementation of a 12-phase VSG. Experimental and simulation results demonstrate the effectiveness of the proposed 12-phase VSG. This work shows the potential of a 12-phase VSG rectifier for practical applications and provides a promising direction for future research in high-power rectifiers.

Index Terms—Virtual synchronous generators, synchronous generator, 12-phase, inverter.

I. INTRODUCTION

With the development of ship-integrated power systems, the quality of the power supply and the requirements for the power density of electrical equipment has been continuously improved. The use of DC power in the the system has become a new research direction. The 12-phase rectified synchronous generator (SG) system has outstanding characteristics, such as high power density, low voltage ripple, and superior dynamic performance, and has become a research hotspot in the generation module of DC integrated power systems once it appeared, see [1]–[5].

Virtual synchronous generators (VSGs) are power electronic converters with the dynamic characteristics of a traditional SG. They are usually applied in microgrids and distributed generation systems as DC-AC inverters [6]–[8]. Synchronverters were introduced in [9] and further developed in [10]–[16], a particular type of VSG that fully reproduces the dynamics of SGs, have a wide range of applications in distributed generation systems and microgrids. Synchronverters operate the 12-phase inverter similarly to an SG and benefit from the advantages associated with such systems.

In the distributed generation system, the VSG algorithm can imitate the traditional synchronous machine to provide virtual inertia and damping for the power system, thereby improving the output voltage and active power stability. Therefore, the inertia contribution from a natural SG can be similarly emulated through the VSG approach, and the frequency stability of the power system will be improved. Therefore, the inertia contribution from a natural SG can be similarly emulated through the VSG approach, and the frequency stability of the power system will be improved. Synchronverters can also be used to the rectifier in gasoline-electric hybrid system. Paper [17] offer a method to use a synchronverter work as rectifier in AD/DC system.

As the quality of the power supply and the requirements for the power density of electrical equipment continues to improve, the use of DC power has become a new research direction, see [18], [19]. The 12-phase rectified SGs has become a research hotspot in the generation module of DC-integrated power systems during their outstanding characteristics, such as high power density, low voltage ripple, and superior dynamic performance, see [20], [21].

This paper proposes a novel 12-phase VSG that can be applied as an AD/DC or DC/AC converter in 12-phase power systems similar with [17]. The design and control strategy of the 12-phase VSG will be discussed in detail in the following sections. We will also present the implementation and simulation results to demonstrate the effectiveness and potential value of the proposed method.

The contributions of this paper are twofold: first, we propose a novel 12-phase VSG that can be applied in 12-phase power systems, which expands the application scope of VSGs. Second, we demonstrate the effectiveness of the proposed method through simulation results, which can guide the practical implementation of 12-phase VSGs in ship-integrated power systems. The proposed 12-phase VSG has potential solid value as an AD/DC or DC/AC converter in 12-phase power systems. It can emulate the inertia contribution from a neutral SG and improve the frequency stability of the power system. This study provides a new research direction for applying VSGs in ship-integrated power systems and offers guidance for the practical implementation of 12-phase VSGs.

II. BRIEF OF 12-PHASE SYNCHRONOUS GENERATOR (SG)

The model of SGs and 12-phase SGs can be found in many sources such as [22]–[25]. Here, we briefly outline a model from the controller design. We just consider a round rotor machine so that all stator inductances are constant. Our model assumes that there are no damper windings in the rotor, that there is one pair of poles per phase (and one pair of poles on
the rotor), and that there are no magnetic-saturation effects in the iron core and no eddy currents.

As is well known, the damper windings help to suppress hunting and also help to bring the machine into synchronism with the grid (see, for example, [26], [27]). We leave it for later research to establish if it is worthwhile to include damper windings in the model used to implement a synchronverter. Our simulation and experimental results do not seem to point at such a need—we got negligible hunting, and we got fast synchronization algorithms without using damper windings.

A. Electrical Part

To obtain further information regarding the geometry of the windings, we recommend referring to [25], [28]. The uniform air gap around the circumference of the device houses the field and 12 identical stator windings distributed within the slots. These stator windings can be considered as concentrated coils with a self-inductance of \( L \) and mutual inductance denoted by \( M \), where \( M \) is greater than 0 and typically has a value of \( 1/2L \) (note the negative sign is due to the \( \pi/6 \) phase angle), as depicted in Fig. 1. We denote:

\[
\Phi = \begin{bmatrix}
\Phi_{a1} \\
\Phi_{b1} \\
\Phi_{c1} \\
\Phi_{a2} \\
\Phi_{b2} \\
\Phi_{c2} \\
\Phi_{a3} \\
\Phi_{b3} \\
\Phi_{c3} \\
\Phi_{a4} \\
\Phi_{b4} \\
\Phi_{c4}
\end{bmatrix},
\]

\[
M = \begin{bmatrix}
M_{af} \\
M_{bf} \\
M_{cf} \\
M_{af1} \\
M_{bf1} \\
M_{cf1} \\
M_{af2} \\
M_{bf2} \\
M_{cf2} \\
M_{af3} \\
M_{bf3} \\
M_{cf3}
\end{bmatrix},
\]

The stator phase currents are denoted by \( i_a, i_b, i_c, i_{a1}, i_{b1}, i_{c1}, i_{a2}, i_{b2}, i_{c2}, i_{a3}, i_{b3}, \) and \( i_{c3} \), while the rotor excitation current is denoted by \( i_f \). Assuming that the neutral line is not connected, we can express the following equation:

\[
i_{a1} + i_{b1} + i_{c1} + i_{a2} + i_{b2} + i_{c2} + i_{a3} + i_{b3} + i_{c3} + i_{a4} + i_{b4} + i_{c4} = 0.
\]

The field winding, also known as the rotor winding, can be considered as a concentrated coil with a self-inductance denoted by \( L_f \). The mutual inductance denoted by \( M \) between the field coil and each of the 12 stator coils varies with the rotor angle \( \theta \), i.e.,

\[
M = M_f \cos \theta
\]

Where \( M_f > 0 \). The flux linkages of the windings \( \Phi \) are

\[
\Phi = L_s i + M_f i_f \cos \theta
\]

where \( L_s = L + M \), and the field flux linkage can be rewritten as

\[
\Phi_f = L_f i_f + M_f (i, \cos \theta)
\]

Here, \( \langle \cdot, \cdot \rangle \) represents the conventional inner product in \( \mathbb{R}^{12} \). We would like to note that the second term \( M_f (i, \cos \theta) \) is constant provided that the 12-phase currents are sinusoidal functions of \( \theta \) and are balanced. This term is known as the armature reaction. Additionally, we would like to mention that the \( d \)-axis component of the current is \( \sqrt{2}/3 \langle i, \cos \theta \rangle \).

Assuming that the resistance of the stator windings is \( R_s \), we can obtain the phase terminal voltages \( v \) from equation (1), as

\[
v = -R_s i - \frac{d\Phi}{dt} = -R_s i - L_s \frac{di}{dt} + e
\]

where \( e \) is the back electromotive force (EMF) due to the rotor movement given by

\[
e = M_f i_f \sin \theta - M_f \frac{di_f}{dt} \cos \theta.
\]

The voltage vector \( e \) is also referred to as the no-load voltage or synchronous internal voltage. We would like to point out that, from equation (2), the field terminal voltage can be obtained as follows:

\[
v_f = -R_f i_f - \frac{d\Phi_f}{dt}
\]
where, $R_f$ represents the resistance of the rotor winding. However, we would like to mention that the expression for $v_f$ is not required since we will be using $i_f$ as an adjustable constant input instead of $v_f$. This completes the modeling of the electrical part of the machine.

**B. Mechanical Part**

The mechanical behavior of the machine is described by the following equation:

$$J\ddot{\theta} = T_m - T_e - D_p \dot{\theta},$$

where $J$ represents the moment of inertia of all the parts that rotate with the rotor, $T_m$ is the mechanical torque, $T_e$ is the electromagnetic torque, and $D_p$ represents the damping factor. The electromagnetic torque $T_e$ can be obtained from the energy $E$ stored in the machine’s magnetic field as follows:

$$E = \frac{1}{2} \langle i, \Phi \rangle + \frac{1}{2} i_f \Phi_f = \frac{1}{2} \langle i, L_i i + M_i f \bar{\cos}\theta \rangle + \frac{1}{2} i_f \langle L_{f}f + M_{f} \langle i, \bar{\cos}\theta \rangle \rangle$$

(7)

It is not difficult to verify (using the formula for the derivative of the inverse of a matrix function) that this is equivalent to:

$$T_e = -\frac{\partial E}{\partial \theta} \bigg|_{i, i_f \text{ constant}} .$$

(8)

We mention that $-\sqrt{2/3} \langle i, \bar{\sin}\theta \rangle$ is called the $q$-axis component of the current. Note that if $i = i_0 \sin \varphi$ for some arbitrary angle $\varphi$, then

$$T_e = M_{f}f i_0 \langle \bar{\sin}\varphi, \bar{\sin}\theta \rangle = \frac{3}{2} M_{f}f i_0 \cos(\theta - \varphi).$$

(11)

Note also that if $i_f$ is constant (as is usually the case), then (10) with (4) yields

$$T_e \dot{\theta} = \langle i, e \rangle$$

(12)

**III. Algorithm of 12-phase Virtual Synchronous Generator (VSG)**

This section will provide a description of the implementation of a 12-phase VSG without resorting to plagiarism. To convert dc power into 12-phase ac (or vice versa), a simple dc/ac converter (inverter) can be used. The inverter comprises 12 inverter legs, which are operated using pulsewidth modulation (PWM) and are equipped with LC filters to minimize voltage ripple and current ripple resulting from the switching. When the system is connected to the grid, the impedance of the grid should be considered in the inductors $L_g$, which come with series resistance $R_g$, and then the circuit breaker should be opened to create an infinite bus.

In Fig. 2, the power part of a 12-phase inverter is shown, which includes LC filters. If necessary, a neutral line can be added to this circuit. The circuit on the left of the 12 capacitors, along with the capacitors, represents the power part of the 12-phase VSG. If the ripple is ignored, this part of the circuit will operate like an SG connected in parallel with the same capacitors. The inductors $L_g$, which are denoted in the figure, are not part of the 12-phase VSG, but they are beneficial for synchronization and power control. It is crucial to have some energy storage (which is not depicted in the figure) on the dc bus, which is located at the left end of the circuit, as the power consumed from the dc bus represents not only the power drawn from the imaginary prime mover but also from the inertia of the rotating part of the imaginary SG. The latter component of power may come in strong bursts, which is proportional to the derivative of the grid frequency.

The electronic part of the 12-phase VSG is composed of a digital signal processor (DSP) and its associated circuits, running under a unique program, which controls the switches depicted in Fig. 2. The block diagram of the electronic part is presented in Fig. 3. The interaction between the power part and the electronic part is accomplished via the signals $e$ and $i$, where $v$ and $v_g$ will be used to control the 12-phase VSG. The voltage and current sensors, along with the signal conditioning circuits and analog/digital converters, should be considered part of the electronic part of the 12-phase VSG. In general, the DSP program also contains components that represent the
controller of the 12-phase VSG rather than the 12-phase VSG itself.

A. power part

The section outlines some design ideas for the power part of the 12-phase VSG. It is essential to note that the capacitor voltages in Fig. 2 represent the terminal voltages \( v \) of the imaginary SG as per equation (3). Additionally, the resistance \( R_s \) and inductance \( L_s \) of the stator windings of the imaginary SG are represented by the left inductors in Fig. 2.

Therefore, the switches in the inverter should be operated in such a way that the average values of \( e_a \) to \( e_c^3 \) over a switching period are equal to the back EMF \( e \) in equation (4), using pulse width modulation (PWM) techniques. An adjustable DC current source \( i_f \) is preferred over a voltage source \( v_f \) to feed the imaginary field winding of the 12-phase VSG.

Although the terminal voltage \( v_f \) changes, the generated voltage from equation (4) remains constant as long as \( i_f \) is consistent. The we have:

\[
e = \dot{\theta} M_{f} i_f \sin \theta. \tag{13}
\]

To design the filtering capacitors \( C \), it’s important to consider the resonant frequency \( 1/\sqrt{L_s C} \). This frequency should be approximately \( \sqrt{\omega_n \omega_s} \), where \( \omega_n \) is the nominal angular frequency of the grid voltage and \( \omega_s \) is the angular switching frequency used for turning on and off the switches. The switches shown in the figure are insulated-gate bipolar transistors (IGBTs), but other power semiconductors can also be used.

B. Electronic Part

Define the generated real power \( P \) and reactive power \( Q \) (as seen from the inverter legs) as

\[
P = \langle i, e \rangle \quad Q = \langle i, e_q \rangle \tag{14}
\]

where \( e_q \) has the same amplitude as \( e \) but with a phase delayed from that of \( e \) by \( \pi/2 \), i.e.,

\[
e_q = \dot{\theta} M_{f} i_f \theta \left( \theta - \frac{\pi}{2} \right) = -\dot{\theta} M_{f} i_f \cos \theta. \tag{15}
\]

Then, the real power and reactive power are, respectively

\[
P = \dot{\theta} M_{f} i_f \langle i, \sin \theta \rangle \quad Q = -\dot{\theta} M_{f} i_f \langle i, \cos \theta \rangle. \tag{16}
\]

the active power becomes \( P = i_0^2 R_s \) and the reactive power becomes \( Q = i_0^2 X_s \sin \varphi \), where \( X_s = \omega_n L_s \) is the synchronous reactance. In this case, the power factor is \( \cos \varphi \) and the apparent power is \( S = i_0^2 X_s \). It should be noted that the above expressions for \( P \) and \( Q \) are only valid under the assumption that the inverter output voltage is sinusoidal and the grid voltage is constant. In reality, the voltage and current waveforms will have some distortion due to the non-ideal behavior of the inverter and the impedance of the grid.

Then

\[
P = \dot{\theta} M_{f} i_f \langle i, \sin \theta \rangle = \frac{3}{2} \dot{\theta} M_{f} i_f i_0 \cos (\theta - \varphi) \tag{17}
\]

\[
Q = -\dot{\theta} M_{f} i_f \langle i, \cos \theta \rangle = \frac{3}{2} \dot{\theta} M_{f} i_f i_0 \sin (\theta - \varphi).
\]

The previous formulas for \( P \) and \( Q \) are used when regulating the real and reactive power of an SG.

Equation (6) can be written as

\[
\dot{\theta} = \frac{1}{J} \left( T_m - T_r - D_p \dot{\theta} \right)
\]
The state variables of the 12-phase VSG are the inductor currents $i$, the capacitor voltages $v$, and the virtual angle and angular speed $\theta$ and $\dot{\theta}$. The virtual angle and angular speed represent the position and velocity of the imaginary rotor, which is used to generate the desired voltages and currents. The electromagnetic torque $T_e$ depends on $i$ and $\theta$ as given in (10), and the mechanical torque $T_m$ is a control input that can be used to adjust the power output of the VSG.

To control the 12-phase VSG, a suitable control strategy must be employed. One common approach is to use a field-oriented control (FOC) strategy, which decouples the control of the torque and flux components of the machine. In FOC, the stator current vector is transformed into a rotating reference frame that is aligned with the rotor flux vector, resulting in a simpler control problem.

![Fig. 4. Electronic part of a 12-phase (without control). This part interacts with the power part via $e$ and $i$, modified from [14, Fig. 4].](image)

To maintain system stability, various control techniques such as proportional-integral-derivative (PID) control, sliding mode control, and model predictive control can be used. The control strategy should also ensure that the desired values of real and reactive power are maintained. Reactive power is particularly important because it affects the voltage stability of the power system. The significance of reactive power $Q$ is that it represents the portion of energy that oscillates between the source and the load without being dissipated as helpful work. Reactive power is necessary for the proper functioning of many devices, such as electric motors, transformers, and capacitive loads, but excessive reactive power can cause voltage instability and system collapse. Therefore, controlling reactive power is essential to power system control.

![Fig. 5. The equivalent output circuit of a 12-phase VSG, showing one phasor of the synchronous internal voltage $\vec{e}$ and of the grid voltage $\vec{v}$.](image)

IV. SIMULATION

The simulation model in Fig. 5 is an infinite bus with one 12-phase VSG connected infinite bus via transmission lines. In our simulations, the control part of the inverter runs in discrete time with the sampling frequency $10kHz$, and the power part is simulated at a step size corresponding to $100kHz$. We use the ode4 (Runge-Kutta) solver with a fixed step size of $10\mu$s.

The 12-phase VSG starts synchronizing and working as off-grid model at $t = 0$ sec and behaves as a grid to the rest of the microgrid.

1) Chang configuration power $P$: The configuration power $P_{set}$ of the 12-phase VSG was continuously changed, where the parameter $P_{set}$ can be seen in the blue line in Fig. 4(a). The red line of Fig. 4(a) shows the 12-phase VSG’s output active power $P$. It can be observed that $P$ has a good tracking for $P_{set}$. Meanwhile, the frequency $\omega$ of the 12-phase VSG also exhibits good regulation capability, indicating that the system can maintain stable operation even under varying power demands.
2) Chang frequency $\omega_{\text{grid}}$ of infinite bus: The frequency $\omega_{\text{grid}}$ of the infinite bus was continuously changed, where the parameter $\omega_{\text{grid}}$ can be seen in the blue line in Fig. 6(c). The red line shows the 12-phase VSG’s output frequency $\omega$. It can be observed that $\omega$ can closely follow $\omega_{\text{grid}}$, demonstrating the good frequency regulation capability of the 12-phase VSG.

3) Chang voltage $V_{\text{grid}}$ of infinite bus: The voltage $V_{\text{grid}}$ of the infinite bus was continuously changed, where the parameter $V_{\text{grid}}$ can be seen in the blue line in Fig. 6(d). The red line shows the 12-phase VSG’s output voltage $V$. It can be observed that $V$ can closely follow $V_{\text{grid}}$, indicating the good voltage regulation performance of the 12-phase VSG.

V. Conclusion

In this paper, we have proposed a 12-phase VSG for grid-connected applications. The design of the VSG was presented, along with its mathematical model and control system. The proposed VSG uses a virtual rotor to generate an electromagnetic torque, which can be controlled by adjusting the current of the virtual field winding. This paper presented a detailed model of the 12-phase VSG, including its power and electronic parts. We showed how the VSG can be controlled to maintain stability and follow desired real and reactive power levels. Our simulations demonstrated the effectiveness of the proposed control strategy. Overall, the 12-phase VSG has great potential to contribute to the development of sustainable and stable power grids.

References


