A REPORT OF MY RECENT STUDY ABOUT "SELF-SYNCHRONIZED SYNCHRONVERTER"

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List of contents:

I. MODELING SYNCHRONOUS MACHINES [1]

II. ADVANTAGES OF BEING SELF-SYNCHRONIZED [2]

III. OVERVIEW OF THE SYNCHRONVERTER TECHNOLOGY [2]

IV. DESIGN AND OPERATION OF A SELF-SYNCHRONIZED SYNCHRONVERTER [2]

V. SIMULATION RESULTS

[1] Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp.1259–1267, Apr. 2011.

[2] Q.-C. Zhong, P. L. Nguyen, Z. Ma, and W. Sheng, "Self-synchronized synchronverters: Inverters without a dedicated synchronization unit," *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 617–630, Feb. 2014.

I. MODELING SYNCHRONOUS MACHINES

The model of synchronous machines can be found in many sources such as [17]–[21]. Most of the references make various assumptions, such as steady state and/or balanced sinusoidal voltages/currents, to simplify the analysis. Here, we briefly outline a model that is a (nonlinear) passive dynamic system without any assumptions on the signals, from the perspective of system analysis and controller design. We 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, [21]). 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

For details on the geometry of the windings, we refer to [18] and [19]. The field and the three identical stator windings are distributed in slots around the periphery of the uniform air gap. The stator windings can be regarded as concentrated coils having self-inductance L and mutual inductance $-M$ ($M > 0$ with a typical value $1/2L$, the negative sign is due to the $2\pi/3$ phase angle), as shown in Fig. 1. The field (or rotor) winding can be regarded as a concentrated coil having self-inductance L_f. The mutual inductance between the field coil and each of the three stator coils varies with the rotor angle θ, i.e.,

$$M_{af} = M_f \cos(\theta)$$
$$M_{bf} = M_f \cos\left(\theta - \frac{2\pi}{3}\right)$$
$$M_{cf} = M_f \cos\left(\theta - \frac{4\pi}{3}\right)$$

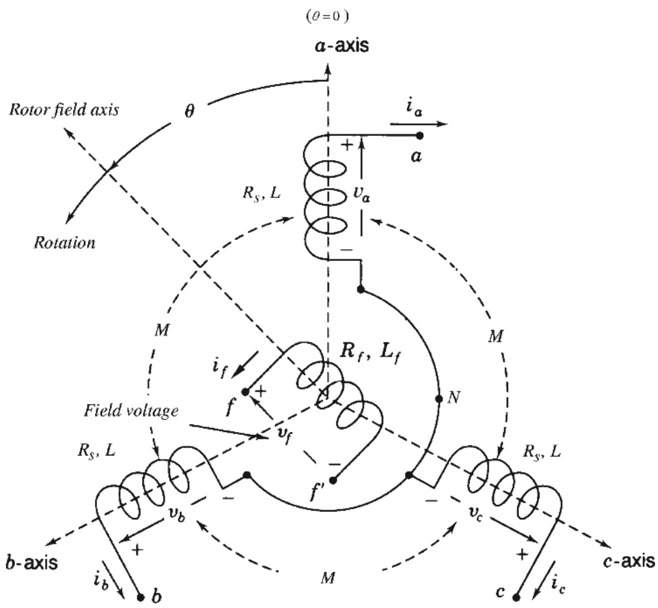

Fig. 1. Structure of an idealized three-phase round-rotor SG, modified from [17, Fig. 3.4].

where $M_f > 0$. The flux linkages of the windings are

$$\Phi_a = Li_a - Mi_b - Mi_c + M_{af}i_f$$

$$\Phi_b = -Mi_a + Li_b - Mi_c + M_{bf}i_f$$

$$\Phi_c = -Mi_a - Mi_b + Li_c + M_{cf}i_f$$

$$\Phi_f = M_{af}i_a + M_{bf}i_b + M_{cf}i_c + L_fi_f$$

where i_a, i_b, and i_c are the stator phase currents and i_f is the rotor excitation current. Denote

$$\Phi = \begin{bmatrix} \Phi_a \\ \Phi_b \\ \Phi_c \end{bmatrix} \qquad i = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$\widetilde{\cos}\,\theta = \begin{bmatrix} \cos\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \qquad \widetilde{\sin}\,\theta = \begin{bmatrix} \sin\theta \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix}.$$

Assume for the moment that the neutral line is not connected, then

$$i_a + i_b + i_c = 0.$$

It follows that the stator flux linkages can be rewritten as

$$\Phi = L_s i + M_f i_f \widetilde{\cos}\,\theta \qquad (1)$$

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

$$\Phi_f = L_f i_f + M_f \langle i, \widetilde{\cos}\,\theta \rangle \qquad (2)$$

where $\langle \cdot, \cdot \rangle$ denotes the conventional inner product in R^3. We remark that the second term $M_f \langle i, \widetilde{\cos}\theta \rangle$ (called armature reaction) is constant if the three phase currents are sinusoidal (as functions of θ) and balanced. We also mention that $\sqrt{2/3}\langle i, \widetilde{\cos}\theta \rangle$ is called the *d*-axis component of the current.

Assume that the resistance of the stator windings is R_s; then, the phase terminal voltages $v = [v_a\, v_b\, v_c]^T$ can be obtained from (1) as

$$v = -R_s i - \frac{d\Phi}{dt} = -R_s i - L_s \frac{di}{dt} + e \qquad (3)$$

where $e = [e_a\, e_b\, e_c]^T$ is the back electromotive force (EMF) due to the rotor movement given by

$$e = M_f i_f \dot{\theta} \widetilde{\sin}\,\theta - M_f \frac{di_f}{dt} \widetilde{\cos}\,\theta. \qquad (4)$$

The voltage vector e is also called no-load voltage or synchronous internal voltage.

We mention that, from (2), the field terminal voltage is

$$v_f = -R_f i_f - \frac{d\Phi_f}{dt} \qquad (5)$$

where R_f is the resistance of the rotor winding. However, we shall not need the expression for v_f because we shall use i_f instead of v_f as an adjustable constant input. This completes the modeling of the electrical part of the machine.

B. Mechanical Part

The mechanical part of the machine is governed by

$$J\ddot{\theta} = T_m - T_e - D_p\dot{\theta} \qquad (6)$$

where J is the moment of inertia of all the parts rotating with the rotor, T_m is the mechanical torque, T_e is the electromagnetic toque, and D_p is a damping factor. T_e can be found from the energy E stored in the machine magnetic field, i.e.,

$$\begin{aligned} E &= \frac{1}{2}\langle i, \Phi\rangle + \frac{1}{2}i_f\Phi_f = \frac{1}{2}\langle i, L_s i + M_f i_f \widetilde{\cos}\,\theta\rangle \\ &+ \frac{1}{2}i_f\left(L_f i_f + M_f\langle i, \widetilde{\cos}\theta\rangle\right) \\ &= \frac{1}{2}\langle i, L_s i\rangle + M_f i_f\langle i, \widetilde{\cos}\,\theta\rangle + \frac{1}{2}L_f i_f^2. \end{aligned}$$

From simple energy considerations (see, e.g., [18] and [22]) we have

$$T_e = \left.\frac{\partial E}{\partial \theta}\right|_{\Phi, \Phi_f \text{constant}}$$

(because constant flux linkages mean no back EMF, all the power flow is mechanical). It is not difficult to verify (using the formula for the derivative of the inverse of a matrix function) that this is equivalent to

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

Thus

$$T_e = -M_f i_f\left\langle i, \frac{\partial}{\partial\theta}\widetilde{\cos}\,\theta\right\rangle = M_f i_f\langle i, \widetilde{\sin}\,\theta\rangle \quad . \qquad (7)$$

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

$$T_e = M_f i_f i_0\langle\widetilde{\sin}\,\varphi, \widetilde{\sin}\,\theta\rangle = \frac{3}{2}M_f i_f i_0\,\widetilde{\cos}(\theta - \varphi)$$

Note also that if i_f is constant (as is usually the case), then (7) with (4) yields

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

C. Provision of Neutral Line

The previous analysis is based on the assumption that the neutral line is not connected. If the neutral line is connected, then

$$i_a + i_b + i_c = i_N$$

where i_N is the current flowing through the neutral line. Then, the formula for the stator flux linkages (1) becomes

$$\Phi = L_s i + M_f i_f \widetilde{\cos}\,\theta - \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} M i_N$$

and the phase terminal voltages (3) become

$$v = -R_s i - L_s \frac{di}{dt} + \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} M \frac{di_N}{dt} + e$$

where e was given by (4). The other formulas are not affected.

As we have seen, the provision of a neutral line makes the system model somewhat more complicated. However, in a synchronverter to be designed in the next section, M is a design parameter that can be chosen to be zero. The physical meaning of this is that there is no magnetic coupling between the stator windings. This does not happen in a physical SG but can be easily implemented in a synchronverter. When we need to provide a neutral line, it is an advantageous choice to take $M = 0$ as it simplifies the equations. Otherwise, the choice of M and L individually is irrelevant; what matters only is that $L_s = L + M$. In the sequel, the model of an SG consisting of (3), (4), (6), and (7) will be used to operate an inverter as a synchronverter.

II. ADVANTAGES OF BEING SELF-SYNCHRONIZED

A synchronverter 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 synchronverter as a self-synchronized synchronverter 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. All the functions of the original synchronverter, such as frequency and voltage regulation, real power, and reactive power control, are maintained. Both simulation and experimental results are presented to validate the control strategy. Experimental results have shown that the proposed control strategy can improve the performance of frequency tracking by more than 65%, the performance of real power control by 83%, and the performance of reactive power control by about 70%.

III. OVERVIEW OF THE SYNCHRONVERTER TECHNOLOGY

A synchronverter is an inverter that mimics a conventional synchronous generator [27], [28]. As a result, grid-connected renewable energy and distributed generation can easily take part in the regulation of system frequency and voltage.

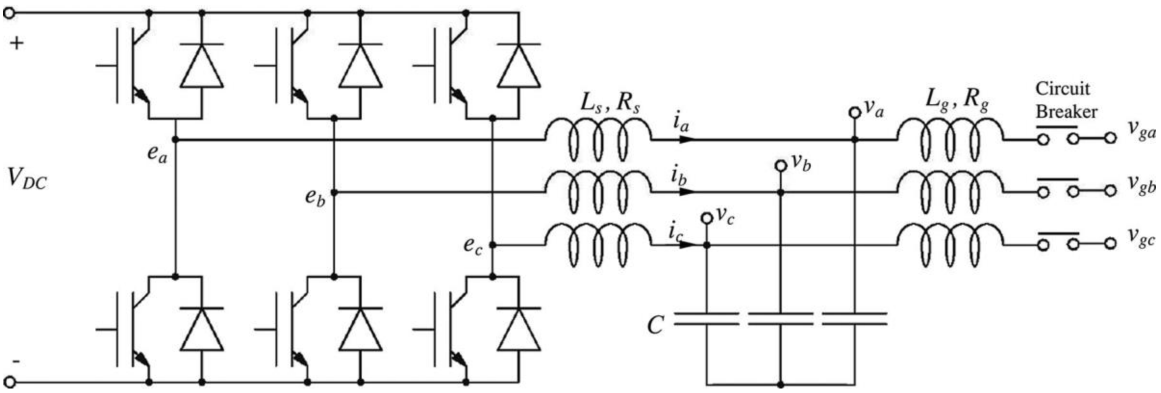

Fig. 3. Power part of a synchronverter.

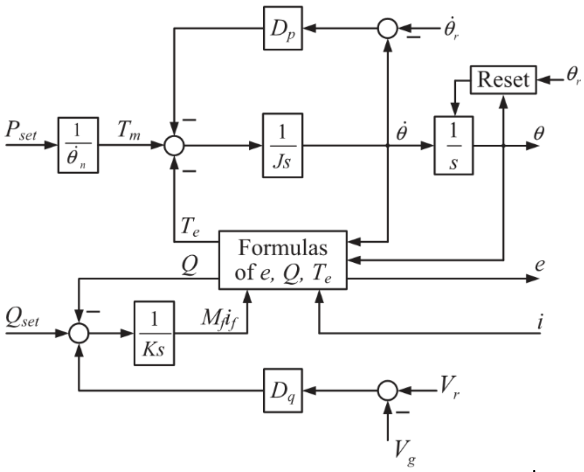

Fig. 4. Electronic part (controller) of a synchronverter, where the provision of the frequency reference $\dot{\theta}_r$, the phase reference θ_r, and the voltage reference V_r, normally via a dedicated synchronization unit, is not shown.

A synchronverter consists of a power part, as shown in Fig. 3, and an electronic part, i.e., the controller, as shown in Fig. 4. It is assumed that the dc bus of the synchronverter is constant. Otherwise, a dc-bus voltage controller, together with an energy storage system if needed, can be introduced to maintain the dc bus voltage constant, e.g., via regulating the reference of the real power for the synchronverter or regulating the power flow into and out of the energy storage system. The controller includes the mathematical model of a three-phase round-rotor synchronous machine described by

$$\ddot{\theta} = \frac{1}{J}(T_m - T_e - D_p\dot{\theta}) \tag{1}$$

$$T_e = M_f i_f \left\langle i, \widetilde{\sin}\,\theta \right\rangle \tag{2}$$

$$e = \dot{\theta} M_f i_f \widetilde{\sin}\,\theta \tag{3}$$

$$Q = -\dot{\theta} M_f i_f \left\langle i, \widetilde{\cos}\,\theta \right\rangle \tag{4}$$

where T_m, T_e, e, θ, and Q are the mechanical torque applied to the rotor, the electromagnetic torque, the three-phase generated voltage, the rotor angle, and the reactive power, respectively. J is the imaginary moment of inertia of all the parts rotating with the rotor. i_f is the field excitation current and M_f is the maximum mutual inductance between the stator windings and the field winding. $\dot{\theta}$ is the virtual angular speed of the machine and also the frequency of the control signal e sent to the pulse width modulation (PWM) generator, and i is the stator current (vector) flowing out of the machine.

$\widetilde{\sin}\theta$ and $\widetilde{\cos}\theta$ are defined as

$$\widetilde{\sin}\theta = \begin{bmatrix} \sin\theta \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}, \quad \widetilde{\cos}\theta = \begin{bmatrix} \cos\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}$$

In this paper, it is assumed that the number of pairs of poles for each phase is 1 and hence the mechanical speed of the machine is the same as the electrical speed of the electromagnetic field.
Similar to the control of a synchronous generator, the controller of a synchronverter has two channels: one for the real power and the other for the reactive power. The real power is controlled by a frequency droop control loop, using the (imaginary) mechanical friction coefficient D_p as the feedback gain. This loop regulates the (imaginary) speed $\dot{\theta}$ of the synchronous machine and creates the phase angle θ for the control signal e. The reactive power is controlled by a voltage droop control loop, using the voltage droop coefficient D_q. This loop regulates the field excitation $M_f i_f$, which is proportional to the amplitude of the voltage generated. Hence, the frequency control, voltage control, real power control, and reactive power control are all integrated in one compact controller with only four parameters.

For grid-connected applications, a synchronization unit is needed to provide the grid information for the synchronverter to synchronize with the grid before connection and for the synchronverter to deliver the desired real and reactive powers after connection.

IV. Design and Operation of a Self-Synchronized Synchronverter

A. A Synchronous Generator (SG) Connected to an Infinite Bus

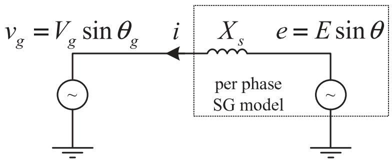

Fig. 5. The per-phase model of an SG connected to an infinite bus.

The per-phase model of an SG, or a synchronverter, connected to an infinite bus is shown in Fig. 5. The generated real power P and reactive power Q are [3], [29]

$$P = \frac{3V_g E}{2X_s}\sin(\theta - \theta_g) \tag{5}$$

and

$$Q = \frac{3V_g}{2X_s}\left[E\cos(\theta - \theta_g) - V_g\right] \tag{6}$$

where V_g is the amplitude of the infinite bus voltage; E is the induced voltage amplitude of the SG which could be controlled by the exciting current/voltage, or $M_f i_f$ in the case of a synchronverter; θ_g and θ are the phases of the grid voltage and of the SG, respectively; and X_s is the synchronous reactance of the SG. The phase difference $\delta = \theta - \theta_g$ is often called the power angle, which is controlled by the driving torque of the turbine. The factor $\frac{1}{2}$ here is because V_g and E are amplitude values, instead of RMS values.

The voltage V_g and the corresponding phase θ_g of the infinite bus can be used as the references for E and θ to generate the preferred P and Q according to (5) and (6). When the driving torque T_m is increased, δ increases and the real power delivered to the grid increases until the electrical power is equal to the mechanical power supplied by the turbine. The maximum δ that the generator is able to synchronize with the grid is $\frac{\pi}{2}$ rad [3]. If the mechanical power keeps increasing and results in a δ that is larger than $\frac{\pi}{2}$ rad, then the rotor of the SG accelerates and loses synchronization with the grid. This should be avoided.

The reactive power Q can be regulated by controlling E, according to (6). When θ and E are controlled to be

$$\begin{cases} E = V_g \\ \theta = \theta_g \end{cases} \tag{7}$$

there is no real power or reactive power exchanged between the connected SG and the grid. In other words, if P and Q are controlled to be zero, then the condition (7) is satisfied and the generated voltage e is the same as the grid voltage v_g. This condition is not common in the normal operation of an SG, but when it is satisfied, the SG can be connected to or disconnected from the grid without causing large transient dynamics. This can be used to synchronize a synchronverter with the grid before connection.

B. The Proposed Controller

The proposed controller for a self-synchronized synchronverter is shown in Fig. 6, after making some necessary changes to the core of the synchronverter controller shown in Fig. 4.

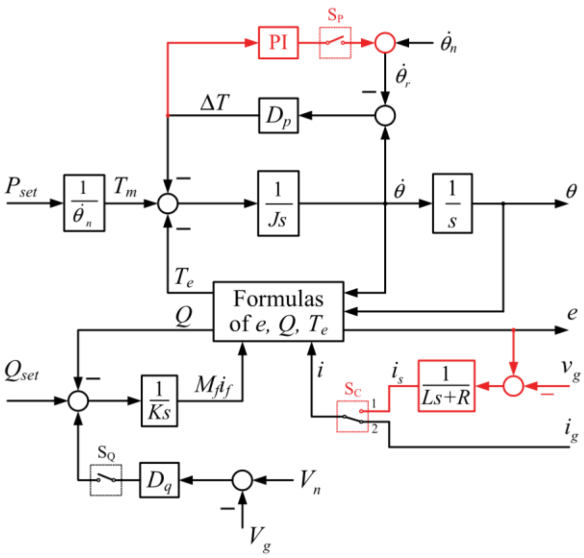

Fig. 6. Proposed controller (electronic part) for a self-synchronized synchronverter.

TABLE I
OPERATION MODES OF A SELF-SYNCHRONIZED SYNCHRONVERTER

Switch S_C	Switch S_P	Switch S_Q	Mode
1	ON	ON	N/A
1	ON	OFF	Self-synchronisation
1	OFF	ON	N/A
1	OFF	OFF	N/A
2	ON	ON	P-mode, Q_D-mode
2	ON	OFF	P-mode, Q-mode
2	OFF	ON	P_D-mode, Q_D-mode
2	OFF	OFF	P_D-mode, Q-mode

It is able to be connected to the grid safely and to operate without the need of a dedicated synchronization unit. There are two major changes made: 1) a virtual current i_s generated from the voltage error between e and v_g is added and the current fed into the controller can be either i_s or the grid current i_g; 2) a PI controller is added to regulate the output ΔT of the frequency droop block D_p to be zero and to generate the reference frequency $\dot{\theta}_r$ for the original synchronverter. In order to facilitate the operation of the self-synchronized synchronverter, three switches S_C, S_P, and S_Q are added to change the operation mode. When Switch S_C is thrown at Position 1 (with S_P turned ON and S_Q turned OFF), the synchronverter is operated under the set mode defined in [28]. If P_{set} and Q_{set} are both 0, then the operation mode is called the self-synchronization mode and the synchronverter is able to synchronize with the grid. When it is synchronized with the grid, the circuit breaker in the power part can be turned on to connect the synchronverter to the grid. When switch S_C is thrown at Position 2, the synchronverter can be operated in four different modes. All the possible operation modes are shown in Table I. In order to safeguard the operation in the self-synchronization mode, S_P can be turned ON and S_Q can be turned OFF automatically whenever switch S_C is thrown at Position 1. In this paper, only the characteristics that are different from the original synchronverter are described, due to the page limit. The details about the original synchronverter, including tuning of parameters, can be found in [28].

C. Operation After Being Connected to the Grid

As mentioned before, the power angle δ of a synchronverter can be controlled by the virtual mechanical torque T_m calculated from the power command P_{set} as

$$T_m = P_{set} / \dot{\theta} \approx P_{set} / \dot{\theta}_n$$

where $\dot{\theta}_n$ is the nominal grid frequency. When S_P is turned ON, ΔT is controlled to be 0 in the steady state via the PI controller. Hence, T_e is the same as T_m and $\dot{\theta}$ is controlled as

$$\dot{\theta} = \dot{\theta}_r = \dot{\theta}_n + \triangle\dot{\theta} \tag{8}$$

where $\triangle\dot{\theta}$ is the output of the PI controller. The power angle δ settles down at a constant value that results in $P = P_{set}$. This operation mode is called the set mode in [28]. In order to differentiate the set mode for real power and reactive power, the set mode for the real power is called the P-mode and the set mode for the reactive power is called the Q-mode in this paper. If $P_{set} = 0$, then $\theta = \theta_g$, in addition to $\dot{\theta} = \dot{\theta}_r$. When the switch S_P is turned OFF, the PI controller is taken out of the loop and the synchronverter is operated in the frequency droop mode (called the P_D-mode in this paper, meaning that the real power P is not the same as P_{set} but deviated from P_{set})[1] with the frequency droop coefficient defined as

$$D_p = -\frac{\triangle T}{\triangle\dot{\theta}} \tag{9}$$

where

$$\triangle\dot{\theta} = \dot{\theta} - \dot{\theta}_n \tag{10}$$

is the frequency deviation of the synchronverter from the nominal frequency. It is also the input to the frequency droop block D_p (because S_P is OFF). This recovers the synchronverter frequency as

$$\dot{\theta} = \dot{\theta}_n + \triangle\dot{\theta}$$

which is the same as (8) but with a different $\triangle\dot{\theta}$. Actually, in both cases, $\dot{\theta}$ converges to the grid frequency $\dot{\theta}_g$ when the power angle δ is less than $\frac{\pi}{2}$ rad, as will be shown below.

According to [28], the time constant $\tau_f = J/D_p$ of the frequency loop is much smaller than the time constant $\tau_v \approx \frac{K}{\dot{\theta} D_q} \approx \frac{K}{\dot{\theta}_n D_q}$ of the voltage loop. Therefore, $M_f i_f$ can be assumed constant when considering the dynamics of the frequency loop. Moreover, according to (5), the real power delivered by the synchronverter $\delta \in (-\frac{\pi}{2}, \frac{\pi}{2})$, T_e (or an SG) is proportional to sinδ. As a result, the electromagnetic torque T_e is proportional to sinδ. For increases when the power angle δ increases and T_e decreases when the power angle δ decreases. If the grid frequency $\dot{\theta}_g$ decreases, then the power angle δ and the electromagnetic torque T_e increase. As a result, the input to the integrator block *1/Js* in Fig. 6 decreases and the synchronverter frequency $\dot{\theta}$ decreases. The process $\delta \in (-\frac{\pi}{2}, \frac{\pi}{2})$ continues until $\dot{\theta} = \dot{\theta}_g$. If the grid frequency increases, then a similar process happens until $\dot{\theta} = \dot{\theta}_g$. Hence, the synchronverter frequency $\dot{\theta}$ automatically converges to the grid frequency $\dot{\theta}_g$ (when) and there is no need to have a synchronization unit to provide $\dot{\theta}_g$ for the synchronverter as the reference frequency.

[1] This means the PI controller is active only in the self-synchronization mode and the set mode (P-mode) but not in the droop mode (P_D-mode).

The proposed controller preserves the reactive power control $\triangle V = V_n - V_g$ channel of the original $\triangle Q = Q$ synchronverter, with the added Switch S_Q to turn ON/OFF the voltage droop function. When S_Q is OFF, $M_f i_f$ is generated from the tracking error between Q_{set} and Q by the integrator with the gain $1/K$. Therefore, the generated reactive power Q tracks the set-point Q_{set} without any error in the steady state regardless of the voltage difference between V_n and V_g. This operation mode is the set mode for the reactive power, called the Q-mode in this paper. When the Switch S_Q is ON, the voltage droop function is enabled and the voltage error is taken into account while generating $M_f i_f$. Hence, the reactive power Q does not track Q_{set} exactly but with a steady-state error $_{\text{set}} - Q$ that is determined by the voltage error $\triangle V$ governed by the voltage droop coefficient

$$D_q = -\frac{\triangle Q}{\triangle V}.$$

This operation mode is the voltage droop mode and is called the Q_D-mode in this paper, meaning that the reactive power is not the same as Q_{set} but deviated from Q_{set}.

D. Synchronization Before Connecting to the Grid

Before the synchronverter is connected to the grid, its generated voltage e (strictly speaking, v) must be synchronized with the grid voltage v_g. Moreover, the amplitude E is also required to be equal to the amplitude V_g and the phase sequence of e and v_g must be the same as well. For a conventional SG, a synchroscope is often used to measure the phase difference between e and v_g so that the mechanical torque is adjusted accordingly to synchronize the SG with the grid. For grid-connected inverters, PLLs are often adopted to measure the phase of the grid voltage so that the generated voltage is locked with the grid voltage.

As mentioned before, the proposed controller shown in Fig. 6 is able to operate the synchronverter under the set mode with $P_{set} = 0$ and $Q_{set} = 0$. As a result, the condition (7) can be satisfied when it is connected to the grid. However, the current i_g flowing through the grid inductor is 0 until the circuit breaker is turned on, and hence, no regulation process could happen. In order to mimic the process of connecting a physical machine to the grid, a virtual per-phase inductor $Ls + R$ is introduced to connect the synchronverter with the grid and the resulting current

$$i_s = \frac{1}{Ls + R}(e - v_g)$$

can be used to replace i_g for feedback so that T_e and Q can be calculated according to (2) and (4). This allows the synchronverter to operate in the P-mode for the real power with $P_{set} = 0$ and in the Q-mode for the reactive power with $Q_{set} = 0$ so that the generated voltage e is synchronized with the grid voltage v_g.

The only difference is that the (virtual) current i_s, instead of the grid current i_g, is routed into the controller via the switch S_C thrown at Position 1. Since the current i_s is not physical, the inductance L and resistance R of the virtual synchronous reactance X_s can be chosen within a wide range. Small values lead to a large transient current i_s to speed up the synchronization process before connection. However, too small L and R may cause oscillations in the frequency estimated. Normally, the L and R can be chosen slightly smaller than the corresponding values of L_s and R_s. Moreover, the ratio $\frac{R}{L}$ defines the cut-off frequency of the filter $\frac{1}{sL+R}$, which determines the capability of filtering out the harmonics in the voltage v_g.

When the virtual current i_s is driven to zero, the synchronverter is synchronized with the grid. Then, the circuit breaker can be turned on at any time to connect the synchronverter to the grid. When the circuit breaker is turned on, the Switch S_C should be turned to Position 2 so that the real current i_g is routed into the controller for normal operation. After the synchronverter is connected to the grid, the switches S_P and S_Q can be turned ON/OFF to achieve any operation mode shown in Table I.

V. SIMULATION RESULTS

The idea described earlier used in order to simulate a self-synchronized synchronverter and study about its behaviour and how it can be improved.

In my simulation, the inverter is considered to be connected to an infinite bus via a step-up transformer. The reason for this is to make the simulation results closer to the real situation. In addition, it seemed that the proposed model of controller is not complete because if induced voltage is to be generated we need angular velocity (ϖ) and also we need excitation ($M_f i_f$) but in the proposed model there is no excitation before applying Q_{set} (with a non-zero value). The solution I have chosen is to add a block that can be considered like an initial field current which the control loop must correct its value during the operation. This initial excitation obviously should be close to its nominal value ($\approx \frac{V_n}{\varpi_n}$). The changed controller is shown in Figure 1. Power part of the simulation is shown in Figure 2.

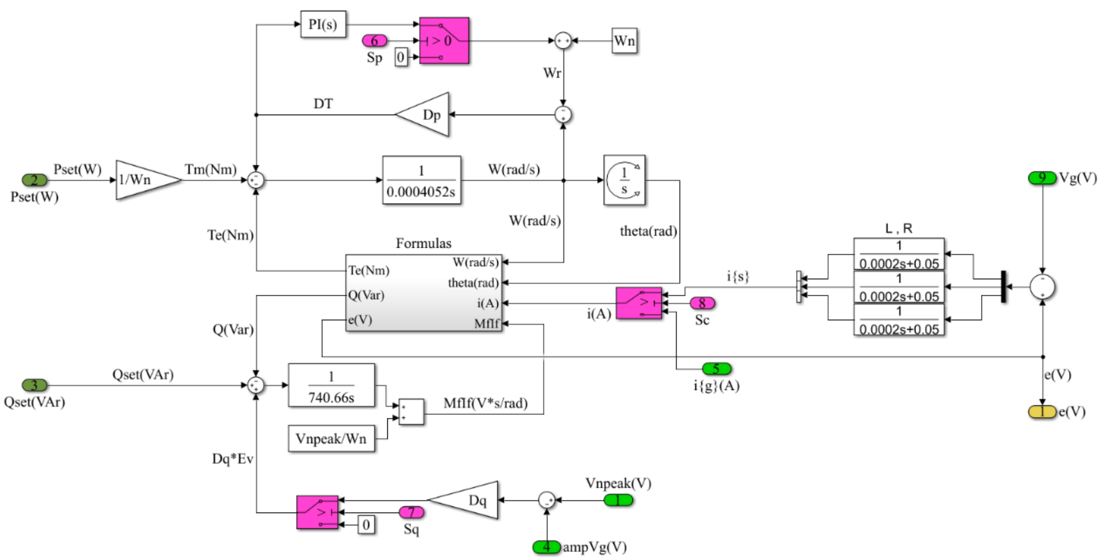

Figure 1 The controller used in my simulation .

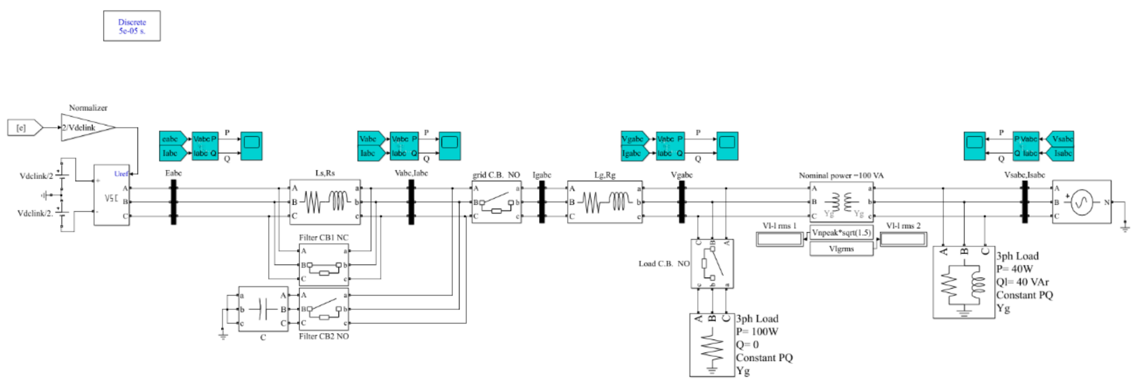

Figure 2 Power part of the simulation including LC filter, a low voltage grid, transformer and infinite bus.

The parameters (shown in TABLE I) of simulated synchronverter are chosen close to the parameters used in the reference papers. The simulation was carried out in MATLAB R2018a with Simulink. The solver used in the simulation was ode23tb with a relative tolerance of 10^{-3} and maximum step size of 0.2 ms.

TABLE I
PARAMETERS OF SYNCHRONVERTER

Name	Value	Comment
Dp	0.2026	
Dq	117.88	
L	0.2 mH	
Lg	0.15 mH	
Ls	0.45 mH	
Pset	80 W	
Qset	60 VAr	
R	0.05 Ohm	
Rg	0.045 Ohm	
Rs	0.135 Ohm	
Vdclink	42 V	
Vlgrms	380 V	
Vnpeak	16.96 V	
Wn	314.1593 rad/s	2*pi*fg
%%Ws	94247.78 rad/s	2*pi*fs
fg	50 Hz	
%%fs	15000 Hz	switching freq.
tf	0.002 s	
tv	0.02 s	
J	tf*Dp	moment of inertia
Ki	9	PI controller
Kp	1	PI controller
Kq	tv*Wn*Dq	

The simulation was started at t = 0 s, with S_C at Position 1, S_P turned ON, S_Q turned OFF and both of *grid C.B.* and *Load C.B.* turned OFF, i.e., in the self-synchronization mode with P_{set} = 0 and Q_{set} = 0. The synchronverter synchronized itself with the grid very quickly. At t = 0.8 s was switched to Position 2 and the grid circuit breaker was turned ON at t = 1 s. The set-point for the real power P_{set} = 80 W was applied at t = 2 s and the set-point for the reactive power Q_{set} = 60 Var was applied at t = 3 s. The drooping mechanism was enabled at t = 4.5 s by turning S_P OFF and S_Q ON. The infinite bus voltage was stepped down to 0.95 pu at t = 5.5 s. The 100 W load was connected to the grid at t = 6.5 s by turning *Load C.B.* ON. The infinite bus voltage was changed back to 1 pu at t = 7.5 s. The simulation was stopped at t = 12 s. The system responses are shown in Figure 3-7 and all of them are shown in Figure 8 together, so the relations between the electrical parameters can be found easily.

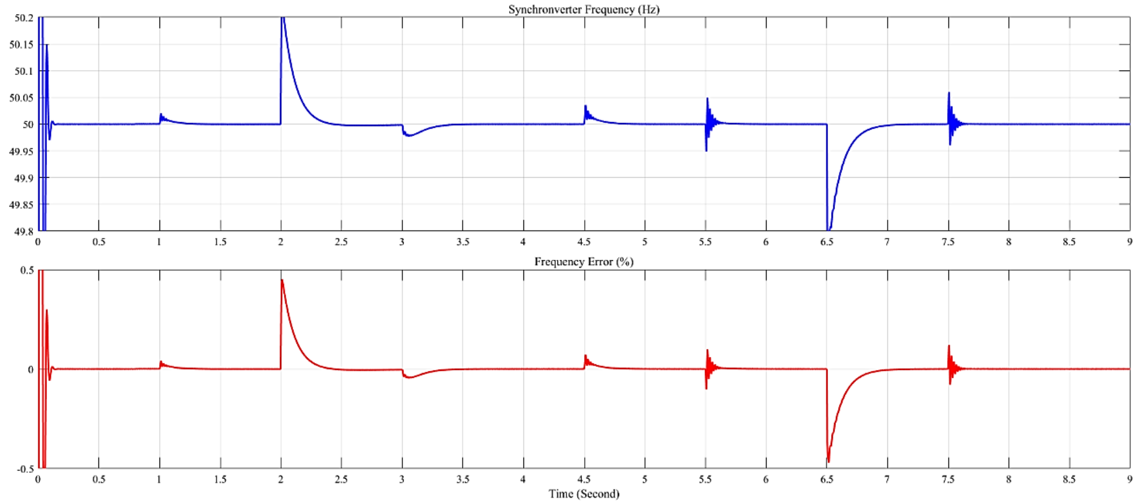

Figure 4 The synchronverter frequency (nominal frequency = 50 Hz).

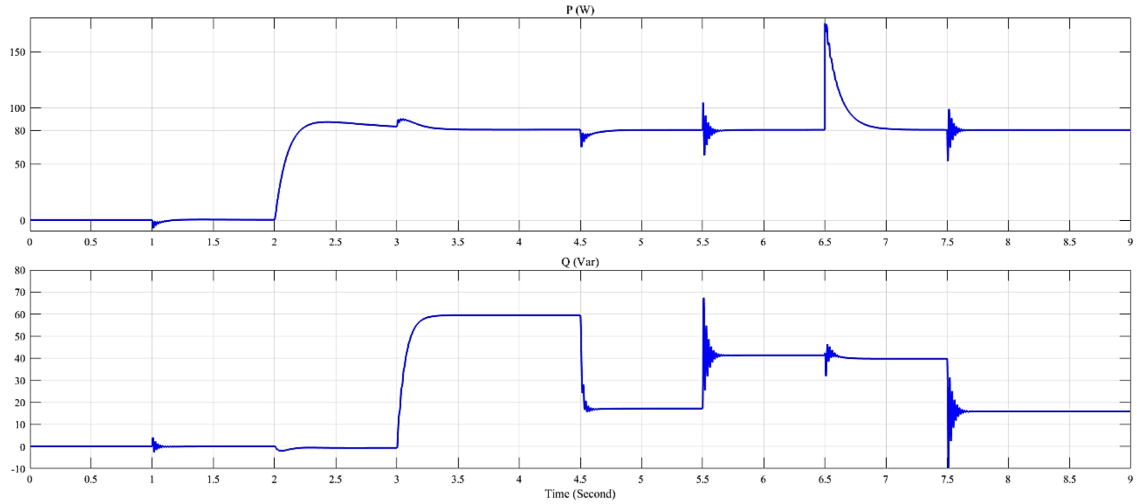

Figure 3 The real and reactive power produced by synchronverter.

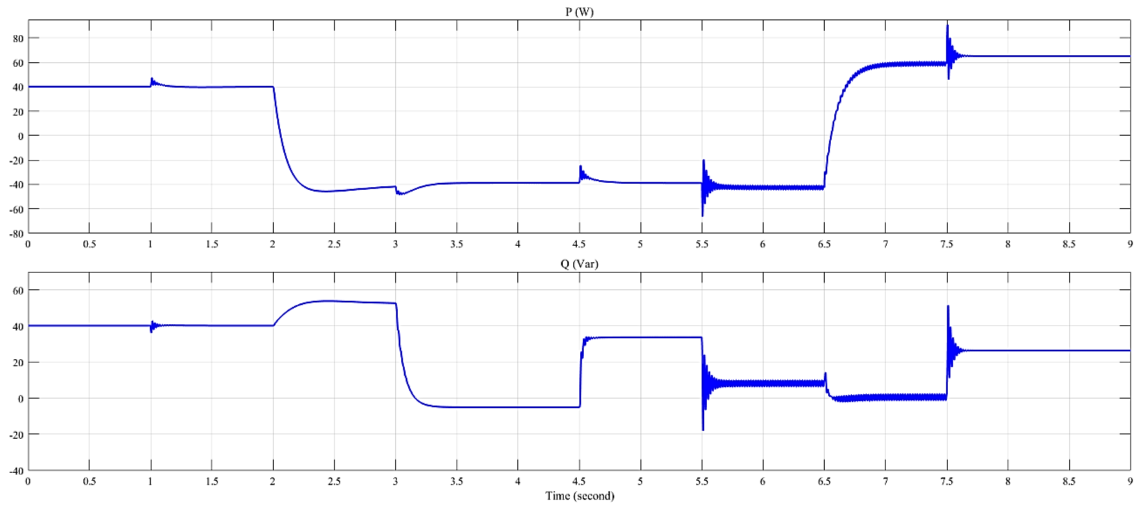

Figure 5 The real and reactive power produced by three-phase voltage source.

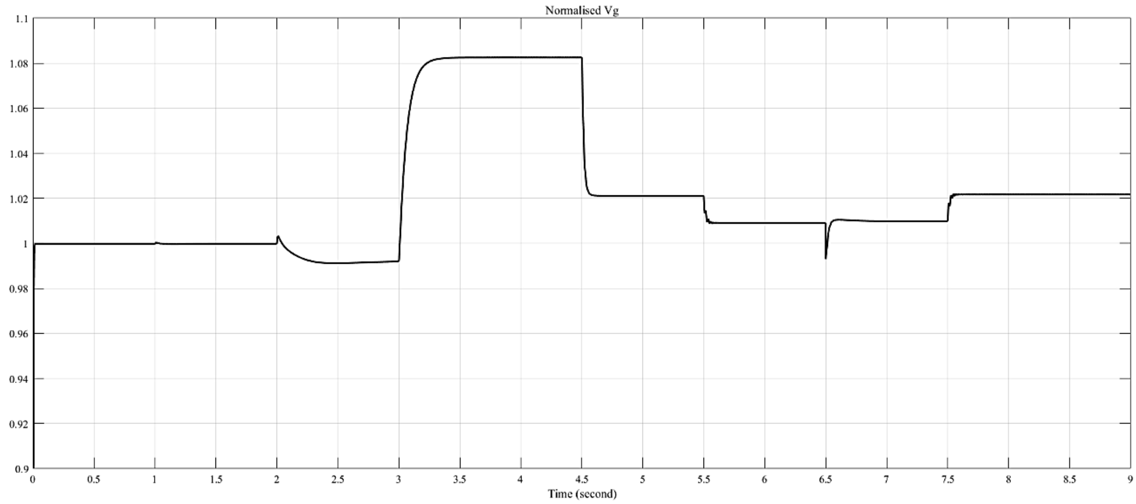

Figure 6 Amplitude of grid voltage (per unit).

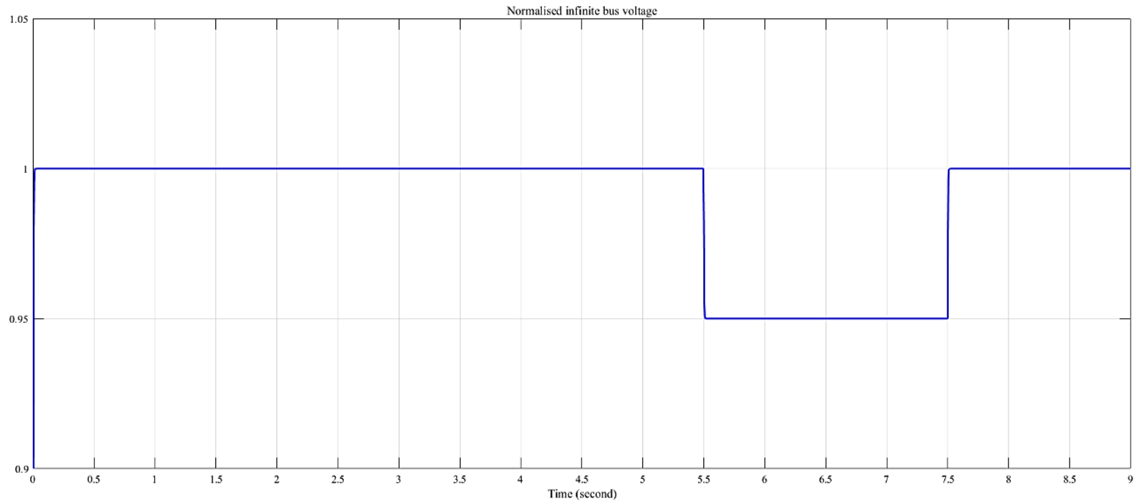

Figure 7 Amplitude of infinite bus voltage (per unit).

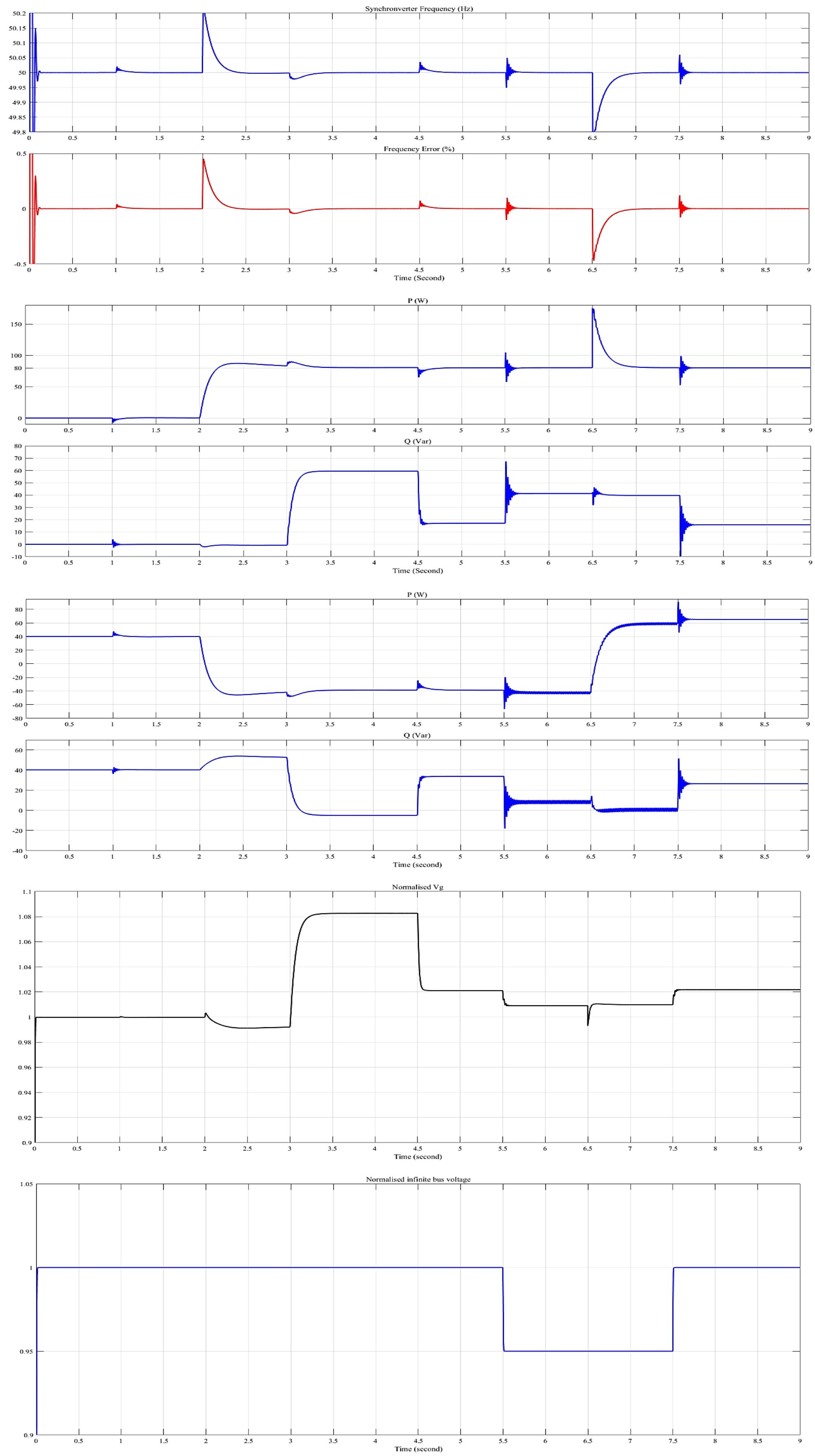

Figure 8 Simulation results.

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