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(71) **Applicants** *(for all designated States except US)*: **ULIVE ENTERPRISES LIMITED** [GB/GB]; Liverpool Science Park, 131 Mount Pleasant, Liverpool, Merseyside L3 5TF (GB). **RAMOT AT TEL AVIV UNIVERSITY LTD** [—/IL]; PO Box 39296, 61392 Tel Aviv (IL).

(72) **Inventors; and**
(75) **Inventors/Applicants** *(for US only)*: **WEISS, George** [—/IL]; 19 Maale Gamla St., 75697 Rishon Le Ziyon (IL). **ZHONG, Qing-Chang** [—/GB]; The University of Liverpool, Department of Electrical Engineering and Electronics, Brownlow Hill, Liverpool, Merseyside L69 3GJ (GB).

(74) **Agent**: **W.P. THOMPSON & CO.**; Coopers Building, Church Street, Liverpool, Merseyside L1 3AB (GB).

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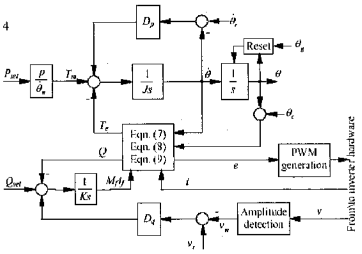
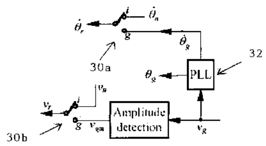
[Continued on next page]

(54) Title: STATIC SYNCHRONOUS GENERATORS

Figure 4



(a) Regulation of real and reactive power



(b) Provision of references, *e.g.*, via PLL

(57) **Abstract**: The invention is concerned with a device and a method for controlling an inverter associated with a power source, which typically will be a distributed power source. The role of an inverter is to modulate the electrical power output, e.g. to provide a three phase AC electrical output at suitable voltage, where the output is to be supplied to a conventional power distribution, grid. The invention involves modelling the behaviour of a synchronous electrical generator. Variables represent the angular position and rotational speed of the virtual rotor (14) of this virtual synchronous generator. The torque electromagnetically exerted on the rotor is calculated from a measured inverter output current, and from a variable representing excitation current in the rotor. Allowing for this and for a notional drive torque applied to the virtual rotor (which in the physical analogue would be supplied by some prime mover such as an engine), as well as for the virtual inertia of the rotor, the angular speed of the virtual rotor is calculated, Using the angular position and rotational speed of the virtual rotor, and allowing for the aforementioned excitation current, it is possible to obtain the emf induced in stators of the virtual generator. On this basis a control signal is generated which causes the inverter to produce an AC output corresponding to that which would be provided by the virtual synchronous generator. A synchronous generator must be regulated, as too must the virtual synchronous generator of the present invention. To this end, the invention provides a feedback loop in which deviation of the rotational speed of the virtual generator rotor from a reference angular speed is detected and is used to adjust the virtual drive torque, thereby to regulate the rotational speed of the rotor and hence the frequency of the AC output and the real power supplied by it.

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STATIC SYNCHRONOUS GENERATORS

The present invention is concerned with a control device for an inverter associated with an electrical power supply. Specifically, the control device causes the power supply and inverter together to mimic in some respects the behaviour of a synchronous electrical generator.

For economic, technical and environmental reasons, more and more distributed energy sources, such as combined heat and power (CHP) plants, and renewable energy sources, such as wind power, solar power, wave and tidal power etc, will play an important role in the future electricity supply. The EU has set a 22% target for the share of renewable energy sources and an 18% target for the share of CHP in electricity generation by 2010. The electrical power system is currently undergoing a dramatic change from centralised generation to distributed generation. Most of these distributed/renewable energy generators produce variable frequency AC sources, high frequency AC, or DC sources, and consequently require DC-AC converters to interface with the public grid. The term "inverter" will be used herein to refer to any device for converting DC to a controlled AC output. Wind turbines, for example, are most effective if free to generate at variable frequency and so they require conversion from variable frequency AC to DC to AC; small gas-turbines with direct drive generators operate at high frequency and require AC to DC to AC conversion; photo-voltaic arrays require DC-AC conversion. More and more inverters will be connected to the grid and will probably dominate the power generation eventually. In all of these cases the same basic inverters are used and need to be controlled to provide high-quality supply waveforms to consumers.

The current paradigm in the control of wind or solar power generators is to extract the maximum power from the power source and inject it all into the power grid. This is a good policy as long as such power sources constitute a negligible part of the grid power capacity, and power fluctuation of the renewable power generators can be compensated by the controllers associated with the grid's large conventional generators. Some of these generators will also take care of overall system stability and fault ride-through. When renewable power generators (especially the solar ones) provide the majority of the grid power, such "irresponsible" behaviour (on their part) will become untenable. Thus, the need will arise to operate them in the same way as conventional power generators function today. This requires first of all large and high efficiency energy storage units, so that the random fluctuations of the prime power source can be filtered out, but it also requires appropriate control of the outputs of the distributed energy sources. There are two options. One is to re-design the whole power system and to change the way it is operated. The other is to find a way for the inverters to be integrated into the existing system and behave in the same way as large synchronous generators (SG), which are the main generators in power plants of today. Apparently, the first option is not economically viable.

It has been proposed that the inverters associated with distributed energy sources should be operated to mimic the behaviour of a synchronous generator (SG). The term "static synchronous generator (SSG)" has been defined by the Institute of Electrical and Electronic Engineers (IEEE) to represent a static, self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multi-phase output voltages, which may be coupled to an AC power system for the purpose of exchanging independently controllable real and reactive power. This was originally defined for one of the shunt-connected controllers in FACTS (flexible AC transmission system). This term is borrowed here to represent inverters which behave like synchronous generators. An SSG has the characteristics of an SG but without rotating parts (hence static). In this way, distributed energy sources can be made to operate on principles well understood in connection with conventional synchronous generators.

A paper entitled "Virtual Synchronous Machine" given at the 9th International Conference on Electrical Power Quality and Utilisation of 9-11 October 2007 by H.P. Beck and R. Hesse describes the basic concept of a virtual synchronous generator, as does the paper "Virtual Synchronous Generators" published in *2008 IEEE Power and Energy Society General – Conversion and Delivery of Electrical Energy in the 21st Century*, pages 1-3, 2008 and written by J. Driesen and J. Visscher. Neither paper describes the practical details of a system required to control a static synchronous generator and this aspect remains problematic.

In accordance with a first aspect of the present invention there is a control device for an inverter, the control device implementing a model of a synchronous generator comprising

variables representing the angular position and rotational speed of a virtual generator rotor,

logic for calculating a virtual electromagnetic torque acting on the virtual generator rotor from measured inverter output current and from a variable representing a virtual excitation current,

logic for calculating the rotational speed of the virtual rotor from the virtual electromagnetic torque and from at least one variable representing a virtual drive torque applied to the virtual generator rotor, and from a parameter representing the rotor's virtual inertia, and

logic for calculating, from the variables representing angular position and rotational speed of the virtual generator rotor and from the variable representing the excitation current, a control signal for controlling the inverter to produce an AC output which corresponds to that of the virtual synchronous generator,

the control device further comprising logic which implements a first feedback loop in which deviation of the rotational speed of the virtual generator rotor from a reference rotational speed is detected and used to adjust the virtual drive torque, thereby to regulate the angular speed of the virtual generator rotor, and hence to regulate frequency of the AC output from the inverter and the real power supplied by the inverter.

In accordance with a second aspect of the present invention, there is a method of controlling an inverter, comprising modelling of a synchronous generator by

representing the angular position and rotational speed of a virtual generator rotor using numerical variables,

measuring the inverter's output current,

calculating a virtual electromagnetic torque acting on the virtual generator rotor from measured inverter output current and from a variable representing a virtual excitation current,

calculating the rotational speed of the virtual rotor from the virtual electromagnetic torque and from at least one variable representing a virtual drive torque applied to the virtual generator rotor, and from a parameter representing the rotor's virtual inertia, and

calculating, from the variables representing angular position and rotational speed of the virtual generator rotor and from the variable representing the excitation current, a control signal for controlling the inverter to produce an AC output which corresponds to that of the virtual synchronous generator,

implementing a first feedback loop in which deviation of the rotational speed of the virtual generator rotor from a reference rotational speed is detected and used to adjust the virtual drive torque, thereby to regulate the rotational speed of the virtual generator rotor, and hence to regulate frequency of the AC output from the inverter and the real power supplied by the inverter.

Specific embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:-

Figure 1 represents the physical construction of an idealised three-phase round-rotor synchronous generator with a single pair of poles per phase;

Figure 2 is a circuit diagram of an inverter for use in implementing the present invention;

Figure 3 is a block diagram representation of a virtual synchronous generator, without control logic;

Figure 4 corresponds to Figure 3 but includes control logic;

Figures 5a to c are graphs of frequency variation over time in a simulation of an SSG according to the present invention;

Figures 6 a and b are graphs of real and reactive power respectively in the simulation;

Figure 7a shows variation of the amplitude of the terminal voltage of the SSG during simulation, and Figure 7b shows, over a much briefer period of time, the sinusoidal variation of the three AC phases of the output from the SSG in a steady state; and

Figures 8a to c are graphs of (a) frequency, (b) real and reactive power and (c) terminal voltage amplitude, all over time and all obtained in a second simulation of the SSG, this time in island mode.

The rest of this description is organised as follows. In Section I, a dynamic model of a synchronous generator is established under no assumptions on the signals. Although the model of an SG has been well described in the literature, the way the model is described here is somewhat fresh. Then, how to implement an inverter to mimic a synchronous generator is described in Section II and a system embodying the present invention for control of an SSG, incorporating frequency and voltage drooping mechanisms for load sharing, is described in Section III, followed by simulation results given in Section IV.

I. MODELLING SYNCHRONOUS GENERATORS

The present embodiment of the invention is based on a mathematical model of a synchronous generator which is considered to be a dynamic system without any assumptions on the signals. Consider the generator arrangement 10 seen in Figure 1, which is a round rotor machine (without damping windings), with p pairs of poles per phase and no saturation effects in the iron core.

A. The electrical part

Three identical stator windings 12a–c are distributed in slots around the periphery of a 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 ½L, the negative sign being due to the $\frac{2\pi}{3}$ phase angle). A field (or rotor) winding 14 can be regarded as a concentrated coil having self-inductance L_f. The mutual inductance between the field winding 14 and each of the three stator coils 12a-c varies with respect to the rotor angle θ as follows:

$$\begin{aligned} M_{af} &= M_f \cos(\theta), \\ M_{bf} &= M_f \cos(\theta - \frac{2\pi}{3}), \\ M_{cf} &= M_f \cos(\theta - \frac{4\pi}{3}). \end{aligned}$$

The flux linkages of the windings are

$$\begin{aligned} \Phi_a &= Li_a - Mi_b - Mi_c + M_{af} i_f, \\ \Phi_b &= -Mi_a + Li_b - Mi_c + M_{bf} i_f, \\ \Phi_c &= -Mi_a - Mi_b + Li_c + M_{cf} i_f, \\ \Phi_f &= M_{af} i_a + M_{bf} i_b + M_{cf} i_c + L_f i_f, \end{aligned}$$

where i_a, i_b and i_c are the stator phase currents and i_f is the rotor excitation current, i.e. the current through the rotor winding 14. Denote

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

and

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

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

$$i_a + i_b + i_c = 0$$

The stator flux linkages can be rewritten as

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

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

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

where $\langle \cdot, \cdot \rangle$ denotes the conventional inner product. The second term $M_f \langle i, \widetilde{\cos}\theta \rangle$ is constant if the three phase currents are sinusoidal and balanced. Assume that the resistance of the stator windings is R_s, then the phase terminal voltages $v = \begin{bmatrix} v_a & v_b & v_c \end{bmatrix}^T$ can be obtained from (1) as

$$v = -R_s i - \frac{d\Phi}{dt} = -R_s i - L_s \frac{di}{dt} + e, \tag{3}$$

where $e = \begin{bmatrix} e_a & e_b & e_c \end{bmatrix}^T$ is the back emf due to the rotor movement given by

$$e = M_f i_f \dot{\theta} \widetilde{\sin}\theta - M_f \frac{di_f}{dt} \widetilde{\cos}\theta. \tag{4}$$

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

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

where R_f is the resistance of the rotor winding. However, in the present treatment we shall not need the expression for v_f because we shall use i_f, instead of v_f, as an adjustable constant input. In other embodiments it would be possible to regulate v_f in place of i_f. This completes modelling the electrical part of the machine.

B. The 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 parts rotating with the rotor, T_m is the mechanical torque upon the rotor due to the driver acting upon it (e.g. the engine driving a power station generator), T_e is the electromagnetic torque on the rotor due to its interaction with the stators and D_p is a damping factor. T_e can be found from the total energy E stored in the machine, which is the sum of the magnetic energy stored in the stator and rotor magnetic fields and the kinetic energy stored in the rotating parts, i.e.

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

Since the mechanical rotor position θ_m satisfies $\theta=p\theta_m$ we have

$$\begin{aligned} T_e &= -\frac{\partial E}{\partial \theta_m} = -p\frac{\partial E}{\partial \theta} \\ &= -pM_f i_f \left\langle i, \frac{\partial}{\partial \theta}\widetilde{\cos}\theta \right\rangle \\ &= pM_f i_f \left\langle i, \widetilde{\sin}\theta \right\rangle . \end{aligned} \tag{7}$$

Note that if $i = i_0\widetilde{\sin}\varphi$ (as would be the case in sinusoidal steady state), then

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

C. *Provision of a neutral Line*

The above analysis is based on the condition that the neutral line is not connected. If the neutral line is connected, then the sum of the three line currents is not 0. Assume

$i_a + i_b + i_c = i_N$

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

$$v = -R_s i - L_s\frac{\mathrm{d}i}{\mathrm{dt}} + \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} M\frac{\mathrm{d}i_N}{\mathrm{dt}} + e,$$

where e is given by (4). The other formulae are not affected.

It is important to note that, in a physical synchronous generator, the provision of a neutral line apparently complicates the system analysis. However, in an SSG to be designed in the next section, M is a design parameter and can hence be chosen as 0. The physical meaning of this is that the mutual inductance M between stator windings is 0. In other words, there is no magnetic coupling between stator windings. This does not happen in a physical synchronous generator but can be easily implemented in an SSG. In the rest of this paper, M is chosen as 0 and the model of a synchronous generator, consisting of equations (3), (4), (5), 6) and (7), will be used to operate an inverter.

II. IMPLEMENTATION OF A STATIC SYNCHRONOUS GENERATOR

In this section, the details of how to implement an inverter as a static synchronous generator will be described. A simple DC/AC converter (inverter) used to convert the DC power supply V_{DC} obtained from renewable/distributed energy sources into three-phase AC (v_a, v_b, v_c) is shown in Figure 2. It consists of three phase legs 16a-c and a three-phase LC filter 18 which is used to suppress the switching noise. If the inverter is to be connected to the grid then a three-phase coupling inductor 20 and a circuit breaker 22 are needed to interface with the grid. The filtering capacitors C should be chosen such that the resonant frequency $\frac{1}{\sqrt{L_s C}}$ is approximately $\sqrt{\omega_n \omega_s}$, where ω_n is the nominal angular frequency of the voltage and ω_s is the angular switching frequency used to turn on/off inverter switches in the phase legs 16a-c (insulated gate bipolar transistors 22 are shown in the figure but other types of switch could be substituted).

An SSG can be implemented according to the mathematical model developed in the previous section. As explained in detail later in this section, an SSG consists of a power part, i.e., the inverter shown in Figure 2, and an electronic part shown in Figure 3. These two parts are interfaced via the signals e and i (and v and v_g to be used for regulating purposes).

A. The electronic part

It is advantageous (but not essential) to assume that the field (rotor) winding is fed by an adjustable DC current source i_f instead of a voltage source v_f. In this case, the terminal voltage v_f varies, but this is irrelevant. As long as i_f is constant, the generated voltage of the virtual generator from (4) is

$$e = \dot{\theta} M_f i_f \widetilde{\sin}\theta. \qquad (8)$$

Define the generated real power P and reactive power Q as

$$P = \langle i, e \rangle \qquad \text{and} \qquad Q = \langle i, e_q \rangle ,$$

where e_q has the same amplitude as e but with a phase delayed from that of e by $\frac{\pi}{2}$, i.e.,

$$e_q = \dot{\theta} M_f i_f \widetilde{\sin}(\theta - \frac{\pi}{2}) = -\dot{\theta} M_f i_f \widetilde{\cos}\theta.$$

Then, the real power and reactive power are, respectively,

$$P = \dot{\theta} M_f i_f \left\langle i, \widetilde{\sin}\theta \right\rangle ,$$

$$Q = -\dot{\theta} M_f i_f \left\langle i, \widetilde{\cos}\theta \right\rangle . \qquad (9)$$

Note that if $i = i_0 \widetilde{\sin}\varphi$ (as would be the case in the sinusoidal steady state), then

$$P = \dot{\theta} M_f i_f \left\langle i, \widetilde{\sin}\theta \right\rangle = \frac{3}{2}\dot{\theta} M_f i_f i_0 \cos(\theta - \varphi),$$

$$Q = -\dot{\theta} M_f i_f \left\langle i, \widetilde{\cos}\theta \right\rangle = \frac{3}{2}\dot{\theta} M_f i_f i_0 \sin(\theta - \varphi).$$

These coincide with the conventional definitions for real power and reactive power (note that the coefficient 3 is because there are three phases). When the voltage and current are in phase, i.e. when $\theta - \phi = 0$, the product of the rms values of the voltage and current gives the real power P. When the voltage and current are $\frac{\pi}{2}$ out of phase, this product gives reactive power Q. Moreover, inductors absorb reactive power with a positive Q (since $\theta - \varphi = \frac{\pi}{2}$, i.e. the voltage leads the current by $\frac{\pi}{2}$) while capacitors generate reactive power with a negative Q (since $\theta - \varphi = -\frac{\pi}{2}$, i.e. the voltage lags the current by $\frac{\pi}{2}$. The above two formulae about P and Q are very important when regulating the real and reactive power of a SG. However, it seems that the formula for reactive power has not been well documented in the literature and the reactive power has not been regarded as an important part of the SG model.

Equation (6) can be written as

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

where the input is the mechanical torque T_m, while the electromagnetic torque T_e depends on i and θ, according to (7). This equation, together with (7), (8) and (9), are implemented in the electronic part of an SSG shown in Figure 3. Thus, the state variables of the SSG are i (which are actual currents), θ and $\dot{\theta}$ (which are a virtual angle and a virtual angular speed). The control inputs of the SSG are T_m and $M_f i_f$. In order to operate the SSG in a useful way, we need a controller that generates the signals T_m and $M_f i_f$ such that system stability is maintained and the desired values of real and reactive power are followed. The significance of Q will be discussed in the next section.

B. The power part

The terminal voltages $v = \begin{bmatrix} v_a & v_b & v_c \end{bmatrix}^T$ given in (3) can be obtained from the (local load) terminals v_a, v_b and v_c of the inverter shown in Figure 2. The inductance L_s and resistance R_s of the inductor can be chosen to represent the stator impedance of a synchronous generator. The switches in the inverter are operated so that the average values of e_a, e_b and e_c over a switching period should be equal to e given in (8) and, hence no special pulse-width-modulation (PWM) techniques are necessary. Also shown in Figure 2 is a three-phase interfacing inductor L_g/R_g and a circuit breaker to facilitate synchronisation/connection with the grid.

III. OPERATION OF AN SSG

A. Frequency drooping and regulation of real power

The terms “real” and “reactive” power are very well known in relation to AC power transmission. The power flow resulting in net transfer of energy, over a complete AC cycle, is the real power. The power flow due to energy which is stored and returned to the source over a cycle (by virtue of capacitance, inductance or equivalent) is the reactive power.

For synchronous generators, the rotor speed is maintained by the prime mover and it is known that the damping factor D_p is due to mechanical friction etc. In a real SG frequency tends to droop (fall) according to the real power delivered. This is important in the existing power distribution grid as it results in SGs sharing load. When the real power demand increases, the speed of the prime mover drops. The speed regulation system of the prime mover then increases the mechanical power, e.g. widening the throttle valve of an engine, so that a new power balance is achieved. This mechanism can be implemented by comparing the virtual angular speed $\dot{\theta}$ e.g. with an angular frequency reference $\dot{\theta}_r$, e.g. the nominal angular speed $\dot{\theta}_n$, before feeding it into the damping block D_p - see the upper part of Figure 4(a). As a result, the damping factor D_p actually behaves as a frequency drooping coefficient, which is defined as the ratio of the required change of torque ΔT to the change of speed (frequency) $\Delta\dot{\theta}$. That is

$$D_p = \frac{\Delta T}{\Delta\dot{\theta}} = \frac{\Delta T}{T_{mn}}\frac{\dot{\theta}_n}{\Delta\dot{\theta}}\frac{T_{mn}}{\dot{\theta}_n};$$

where T_{mn} is the nominal mechanical torque. Note that in much of the literature, D_p is defined as $\frac{\Delta\dot{\theta}}{\Delta T}$. The mechanical torque T_m can be obtained from a set point of real power P_{set} after dividing by the nominal mechanical speed $\frac{\dot{\theta}_n}{p}$. This completes the feedback loop for real power; see the upper part of Figure 4(a). Because of the built-in frequency drooping mechanism, an SSG automatically shares the load with other inverters of the same type connected on the same bus. The power regulation loop is very simple because no mechanical devices are involved and no measurements are needed for real power regulation (all variables are available internally).

The regulation mechanism of the real power (torque) shown in the upper part of Figure 4(a) has a cascaded control structure, of which the inner loop is the frequency loop and the outer loop is the real power (torque) loop. The time constant of the frequency loop is

$$\tau_f = \frac{J}{D_p}.$$

In other words, J can be chosen as

$$J = D_p \tau_f.$$

Because there is no delay involved in the frequency drooping loop, the time constant τ_f can be made much smaller than that of a physical synchronous generator. In order to make sure that the frequency loop has a quick response so that it can track the frequency reference quickly, τ_f should be made small. Hence, for a given frequency drooping coefficient D_p, J should be made small. This indicates that it is not necessary to have a large inertia for the virtual physical synchronous generator, although a larger inertia means that more energy can be stored. In other words, the energy storage function of an SSG can, and should, be decoupled from the inertia.

B. Voltage drooping and regulation of reactive power

The regulation of reactive power Q flowing out of the SSG can be realised similarly. Define the voltage drooping coefficient D_ρ as the ratio of the required change of reactive power ΔQ to the change of voltage Δv, i.e.

$$D_q = \frac{\Delta Q}{\Delta v} = \frac{\Delta Q}{Q_n} \frac{v_n}{\Delta v} \frac{Q_n}{v_n},$$

where Q_n is the nominal reactive power, which can be chosen as the nominal power, and v_n is the nominal amplitude of terminal voltage v. The regulation mechanism for the reactive power can be realised as shown in the lower part of Figure 4(a). The difference between the voltage reference v_r, e.g. the amplitude v_n of the nominal voltage, and the amplitude v_m of the actual terminal voltage v is amplified by the voltage drooping coefficient D_q before adding to the difference between the set point Q_{set} and the current reactive power Q, which is calculated according to (9). The resulting signal is then fed into an integrator with a gain $\frac{1}{K}$ to generate $M_f i_f$ (here, K is dual to the inertia J). It is important to note that there is no need to measure reactive power Q as it is available internally.

The regulation mechanism of the reactive power shown in the lower part of Figure 4(a) has a cascaded control structure, if the effect of the LC filter 18 is ignored or compensated (which means $v = e$). The inner loop is the (amplitude) voltage loop and the outer loop is the reactive power loop. The time constant of the voltage loop is

$$\tau_v = \frac{K}{\dot{\theta} D_q} \approx \frac{K}{\dot{\theta}_n D_q}$$

as the variation of $\dot{\theta}$ is very small. Hence, K can be chosen as

$$K = \dot{\theta}_n D_q \tau_v .$$

The amplitude v_m of the terminal voltage v can be obtained as follows. Assume that $v_a = v_{am}\sin\theta_a$, $v_b = v_{bm}\sin\theta_b$ and $v_c = v_{cm}\sin\theta_c$, then

$$\begin{aligned} v_a v_b + v_b v_c + v_c v_a &= v_{am} v_{bm} \sin\theta_a \sin\theta_b + v_{bm} v_{cm} \sin\theta_b \sin\theta_c + v_{cm} v_{am} \sin\theta_c \sin\theta_a \\ &= \frac{v_{am} v_{bm}}{2}\cos(\theta_a - \theta_b) + \frac{v_{bm} v_{cm}}{2}\cos(\theta_b - \theta_c) + \frac{v_{cm} v_{am}}{2}\cos(\theta_c - \theta_a) \\ &\quad -\frac{v_{am} v_{bm}}{2}\cos(\theta_a + \theta_b) - \frac{v_{bm} v_{cm}}{2}\cos(\theta_b + \theta_c) - \frac{v_{cm} v_{am}}{2}\cos(\theta_c + \theta_a). \end{aligned}$$

When the terminal voltages are balanced, i.e., when $v_{am} = v_{bm} = v_{cm} = v_m$ and $\theta_b = \theta_a - \frac{2\pi}{3} = \theta_c + \frac{2\pi}{3}$, then the last three terms in the above equality are balanced, having a doubled frequency. Hence,

$$v_a v_b + v_b v_c + v_c v_a = -\frac{3}{4} v_m^2,$$

and the amplitude v_m of the actual terminal voltage v can be obtained as

$$v_m = \frac{2}{\sqrt{3}} \sqrt{-(v_a v_b + v_b v_c + v_c v_a)}. \qquad (10)$$

In real implementation, a low-pass filter is needed to filter out the ripples at the doubled frequency as the terminal voltages may be unbalanced. This also applies to T_e and Q.

C Operation modes of an SSG and its synchronisation

As shown above, an SSG can be operated in the same way as a synchronous generator under normal working conditions. An important process related to an

SSG or SG is the synchronisation procedure, prior to connection of the SSG/SG to another SSG/SG or to the public grid. This procedure involves bringing the terminal voltage v to be (almost) the same as the grid voltage v_g on the other side of the circuit breaker 22, which means the same amplitude, the same frequency and the same phase angle. It is not an easy task to implement this for conventional SGs as this procedure involves much external equipment. For the SSG developed in this paper, this is relatively easy as the variables required are all available internally. A change of operation mode from island mode (in which the SSG operates without connection to a power grid) to grid-connected mode or vice verse can be implemented via a *controlled* multi-pole-double-throw (MPDT) switch 30a, b, Figure 4, with one throw for island mode (labelled as i) and the other for grid-connected mode (labelled as g), to change the frequency/voltage references. Whether an SSG works in island mode or grid-connected mode, the status of the MPDT switch 30a, b, is determined by the presence of the grid voltage and the status of a mode switch which sets the operation mode of the SSG. See Table 1 for the logic of operation. The default position of the mode switch is at "grid-connected" and it is turned to "island" when there is a fault. In grid-connected mode, the frequency/voltage references are set as the corresponding values of the grid voltage v_g and the integrator that produces phase θ, the electrical angle between the rotor field and the phase-a field, is reset according to the grid phase when the circuit breaker is not turned on. There are many ways to obtain the grid frequency $\dot{\theta}_g$ and phase θ_g; one of them is to use a phase-locked loop (PLL), as shown at 32 in Figure 4. The amplitude v_{gm} of the voltage v_g on the grid side of the circuit breaker can be calculated according to (10), replacing v with v_g. In island mode, the references are set to the corresponding nominal values

$$\dot{\theta}_r = \dot{\theta}_n, \quad v_r = v_n.$$

When the voltage across the circuit breaker is small, the SSG can provide a green (go-ahead) signal for the operator to turn on the circuit breaker (it can be set to turn on automatically). The circuit breaker is allowed to be turned on in two cases: (1) when the MPDT switch i_g is set at Throw g, i.e., when the grid voltage is present and the mode switch is turned at grid-connected mode; (2) when the grid voltage is not present and the mode switch is turned at island mode, which allows parallel operation of multiple inverters (to be discussed in more detail later).

After the circuit breaker is turned on, as the amplitude of the terminal voltage is set to follow that of the grid voltage, the voltage drooping mechanism disappears and the terminal voltage amplitude is determined by the grid. The frequency also

Table I

THE LOGIC OF OPERATION FOR AN SSG (TRUTH TABLE)

Inputs		Outputs	
Presence of v_g	Mode switch	MPDT i_g	Circuit breaker to be turned on
Yes	island	i	Prohibited
Yes	grid-connected	g	Allowed after synchronisation
No	island	i	Allowed without synchronisation
No	grid-connected	i	Prohibited

follows that of the grid. The integrator that produces phase θ is no longer reset according to the grid phase and hence real power can be regulated. Multiple SSGs can be connected to the grid in the same way. Because of the presence of a grid, P_{set} and Q_{set} should be set at the values requested by the grid operator. In this case, local load can be connected to the inverter terminals v_a, v_b and v_c to form a micro grid. In order for the frequency and the voltage to follow those of the grid, it is important to choose small τ_f and τ_v.

If there is no grid voltage present, then an SSG works in island mode and the real power and reactive power delivered by the SSG are determined by the load. If there is more than one SSG to be connected in parallel, then the first one that is put into operation works with the mode switch set at "island" to establish the system frequency and voltage. Note that in this case the circuit breaker can be turned on straightaway, according to the logic of operation set in Table 1, so that the voltage is present on the other side of the circuit breaker, which allows other SSGs to synchronise with it and to join the system under the grid-connected mode. In this case, P_{set} and Q_{set} should be set at 0 as the power delivered is determined by the local load.

D. Some practical issues

It is necessary to measure the terminal voltage v for the voltage drooping, the current i flowing out of the inverter for the calculation of T_e P and Q the grid voltage v_g for synchronisation. A complete SSG consists of a power part shown in

Figure 2, and a complete electronic part shown in Figures 4(a) and (b), which are interfaced with each other via $\dot{\theta}_r$, θ_g and v_r. It can be seen that the nominal angular frequency $\dot{\theta}_n$ and voltage (amplitude) v_n are all set in the system via the frequency reference $\dot{\theta}_r$ and voltage reference v_r. A resetting mechanism is added to the integrator generating θ to prevent numerical overflow under normal working condition and to obtain the same phase as the grid voltage during synchronisation. The phase of the SSG can be reset as 0 when the grid voltage crosses 0, which is impossible for a physical synchronous generator. Another important mechanism is to add a constant phase shift θ_c to the phase θ so that the delay in the PWM switching process and the phase shift of the LC filter can be compensated, which brings the phase difference between v and v_g to be minimal during synchronisation. The electronic part of an SSG can be implemented in a microcontroller (this is normally the case) and, hence, it is possible to use different values of $D_p (D_q)$ and J (K) when the SSG works in different modes.

Some guidelines on choosing D_p and J are: (1) D_p should be chosen to satisfy the frequency regulation requirement; (2) J should be chosen to achieve the desired frequency-loop time constant τ_f.

Some guidelines on choosing D_q and K are: (1) D_q should be chosen to satisfy the voltage regulation requirement; (2) K should be chosen to achieve the desired voltage-loop time constant τ_v.

For relatively small inverters, D_p *and* (D_q) should be chosen so that the full step change of real and reactive power should not cause noticeable change in the frequency and voltage.

Table II

PARAMETERS OF THE INVERTER-INFINITE BUS SYSTEM

Parameters	Values		Parameters	Values
L_s	0.15 mH		L_g	0.0534 mH
R_s	0.045 Ω		R_g	0.06 Ω
C	22 μF		Frequency	50 Hz
R (parallel to C)	1000 Ω		Voltage (line-line)	17 Vrms
Rated power	100 W		Initial grid phase	0°
Inertia J	0.01 Kgm^2		K	13580

IV. SIMULATION RESULTS

The idea described above has been verified with simulations. The parameters of the inverter for carrying out the simulations are given in Table II.

The frequency drooping coefficient is chosen as $D_p = 0.2432$ so that the frequency drops 0.5% when the torque (power) increases 100%. The virtual inertia is chosen as J=0.01 so that no-load time constant is roughly τ_f=0.04 second. The simulation was carried out in MATLAB® 7.4 with Simulink™. The solver used in the simulations is ode23tb with a relative tolerance 10^{-3} and a maximum step size of 10^{-4} second.

A. Grid-connected mode: Without voltage drooping

The inverter is connected to the grid via a circuit breaker and a step-up transformer. In this case, $D_q = 0$. The SSG was connected to the grid at t=1 second. The real power P=80W was applied at t=2 second by suitably setting P_{set} and the reactive power Q=60 Var was applied at t=3.5 second by means of Q_{set}. In the simulations, a model of the LC filter and the interfacing inductor was included in the control algorithm so that it is possible to assume that the inverter was connected to the grid virtually inside the controller all the time (although the converter was not connected to the grid physically until t=1 second). The initial state of $\dot{\theta}$ was set at 100π. The drooping coefficient D_p was reduced to 1% of its original value before any real power was applied and the inertia was reduced so that the no-load time constant WAS about 2 cycles before the inverter was connected to the grid.

The response of the SSG frequency is shown in Figure 5. The SSG quickly synchronised with the grid in about 10 cycles. No visible dynamics were seen after the SSG was connected to the grid at t=1 second. When the SSG was requested to deliver 80W real power to the grid, the frequency of the SSG increased and then returned to the grid frequency 50Hz after about 20 cycles. When the SSG was requested to deliver 60Var reactive power to the grid, the frequency of the SSG decreased slightly and then returned to the grid frequency quickly.

The output power of the SSG is shown in Figure 6. During the synchronisation period, there were some oscillations in the power (which is inside the controller as the breaker is not yet turned on and hence it does not cause any problem). Before the SSG was requested to deliver power (i.e., before t=2 seconds), the real power and reactive power were zero. Then, the real power delivered to the grid gradually increased to the set point 80W. During this transient process, the SSG initially took reactive power from the grid but returned to normal. At t=3.5 second, the reactive power delivered by the SSG increased to the setpoint 60Var gradually. During this period, the real power increased slightly but then returned to the set point 80W very quickly.

B. Island mode: With voltage drooping

In this case, P_{set} and Q_{set} were set at *0* and D_q=144.0876 so that the voltage changes 5% if the reactive power changes 100%. The island mode is simulated by setting R_g=10000Ω and L_g=0. The resistor R connected in parallel with C is reduced to 5Ω at t=2 second and C is increased to 660μF at t=3.5 second. The current i is not fed back to the system before t=0.1 second, i.e., before the voltage v is established.

The frequency curve is shown in Figure 8(a). After the real power applied at t=2 second, the frequency reduced to 49.855Hz, which further reduced to 49.842Hz after the reactive load was applied. The real power and reactive power are shown in Figure 8(b). The change of the load caused some fast oscillations (spikes) in the curve. The amplitude of the terminal voltage is shown in Figure 8(c). Although there were some fast oscillations (spikes) in the voltage when the load was changed, the voltage fell into the close range of the nominal value very quickly.

CLAIMS

1. A control device for an inverter, the control device implementing a model of a synchronous generator comprising

variables representing the angular position and rotational speed of a virtual generator rotor,

logic for calculating a virtual electromagnetic torque acting on the virtual generator rotor from measured inverter output current and from a variable representing a virtual excitation current,

logic for calculating the rotational speed of the virtual rotor from the virtual electromagnetic torque and from at least one variable representing a virtual drive torque applied to the virtual generator rotor, and from a parameter representing the rotor's virtual inertia, and

logic for calculating, from the variables representing angular position and rotational speed of the virtual generator rotor and from the variable representing the excitation current, a control signal for controlling the inverter to produce an AC output which corresponds to that of the virtual synchronous generator,

the control device further comprising logic which implements a first feedback loop in which deviation of the rotational speed of the virtual generator rotor from a reference rotational speed is detected and used to adjust the virtual drive torque, thereby to regulate the angular speed of the virtual generator rotor, and hence to regulate frequency of the AC output from the inverter and the real power supplied by the inverter.

2. A control device as claimed in claim 1 further comprising logic implementing a second feedback loop in which deviation of a measured inverter output voltage from a reference value is detected and used in adjustment of the virtual excitation current, thereby to regulate the inverter output voltage.

3. A control device as claimed in claim 2 in which the deviation of reactive power from a reference level is detected and is used in adjustment of the virtual excitation current in the second feedback loop, thereby to regulate reactive power supplied by the inverter.

4. A control device as claimed in any preceding claim in which the first feedback loop receives as an input a nominal virtual drive torque, this being added to a correction to the virtual drive torque provided through the feedback loop to form the virtual drive torque and added to the virtual electromagnetic torque to determine the total virtual torque acting upon the virtual generator rotor.

5. A control device as claimed in claim 4 in which the total virtual torque acting upon the virtual rotor is integrated and divided by a virtual rotor momentum to determine the rotational speed of the virtual generator rotor.

6. A control device as claimed in claim 5 in which the difference between the rotational speed of the virtual generator rotor and a reference rotational speed,

corresponding to the desired AC output frequency of the inverter, is multiplied by a frequency drooping coefficient to form the correction to the virtual drive torque.

7. A control device as claimed in any of claims 4 to 6 in which the nominal virtual drive torque is determined by dividing an input representing desired inverter real output power by a value representing the angular speed of the AC inverter output.

8. A control device as claimed in any preceding claim in which the virtual electromagnetic torque is calculated as the product of the measured inverter output current, the virtual excitation current, and a sin or cosine function of the angular position of the virtual generator rotor.

9. A control device as claimed in any preceding claim in which the inverter is controlled to provide an alternating output voltage determined from the model of the synchronous generator.

10. A control device as claimed in claim 9 in which the alternating output voltage to be provided by the inverter is calculated as the product of the rotational speed of the virtual generator rotor, the virtual excitation current, and a sin or cosine function of the angular position of the virtual generator rotor.

11. A control device as claimed in claim 10 in which the control signal for controlling the inverter is pulse width modulated to cause the inverter to provide the calculated alternating output voltage.

12. A control device as claimed in any claim 2, or claim 3, or in any subsequent claim when dependent on claim 2 or claim 3, in which, in the second feedback loop, the difference between reactive power and its reference level is added to a voltage drooping variable representing the deviation of the measured inverter output voltage from its reference value and is integrated to establish the virtual excitation current.

13. A control device as claimed in claim 12 in which the voltage drooping variable is established by multiplying the deviation of the measured inverter output voltage from its reference value by a voltage drooping coefficient.

14. A control device as claimed in claim 13 in which the measured inverter output voltage is the amplitude of the inverter's AC output.

15. A control device as claimed in any preceding claim for controlling an inverter which is to be connected to a power distribution grid, the control device comprising a device for detecting the AC frequency of the power distribution grid and using same to form the reference rotational speed used in the first feedback loop to control rotational speed of the virtual generator rotor.

16. A control device as claimed in claim 15 further comprising a device for detecting the AC phase of the power distribution grid, and for resetting the angular position of the virtual generator rotor to match the phase of the grid prior to connection of the inverter to the grid.

17. A control device as claimed in claim 16 in which the frequency and phase of the power distribution grid are obtained using a phase locked loop.

18. An apparatus for regulating supply of electrical power from a power source, the apparatus comprising a control device as claimed in any preceding claim operatively connected to an inverter, and the inverter having at least one output line connectable via a circuit breaker to a power supply grid.

19. An apparatus as claimed in claim 18 comprising LC smoothing circuitry connected between the inverter and the circuit breaker.

20. An apparatus as claimed in claim 18 or claim 19 further comprising a coupling inductance in series between the inverter and the circuit breaker.

21. A method of controlling an inverter, comprising modelling of a synchronous generator by

representing the angular position and rotational speed of a virtual generator rotor using numerical variables,

measuring the inverter's output current, calculating a virtual electromagnetic torque acting on the virtual generator rotor from measured inverter output current and from a variable representing a virtual excitation current,

calculating the rotational speed of the virtual rotor from the virtual electromagnetic torque and from at least one variable representing a virtual drive torque applied to the virtual generator rotor, and from a parameter representing the rotor's virtual inertia, and

calculating, from the variables representing angular position and rotational speed of the virtual generator rotor and from the variable representing the excitation current, a control signal for controlling the inverter to produce an AC output which corresponds to that of the virtual synchronous generator,

implementing a first feedback loop in which deviation of the rotational speed of the virtual generator rotor from a reference rotational speed is detected and used to adjust the virtual drive torque, thereby to regulate the rotational speed of the virtual generator rotor, and hence to regulate frequency of the AC output from the inverter and the real power supplied by the inverter.

22. A method as claimed in claim 21 further comprising implementing a second feedback loop in which deviation of a measured inverter output voltage from a reference value is detected and used in adjustment of the virtual excitation current, thereby to regulate the inverter output voltage.

23. A method as claimed in claim 23 in which the deviation of reactive power from a reference level is detected and is used in adjustment of the virtual

excitation current in the second feedback loop, thereby to regulate reactive power supplied by the inverter.

Figure 1

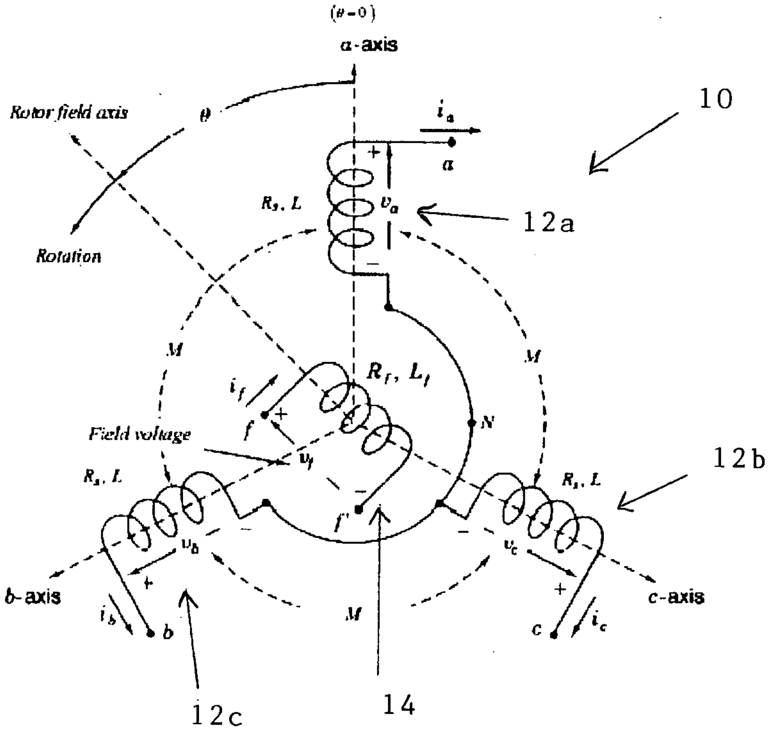

(θ=0)
a-axis
Rotor field axis
θ
Rotation
i_a
a
+
v_a
−
R_s, L
10
12a
M
M
M
R_f, L_f
i_f
f
+
Field voltage
v_f
−
f'
N
R_s, L
R_s, L
12b
v_b
+
−
b-axis
i_b
b
v_c
+
−
c-axis
c
i_c
12c
14

Figure 2

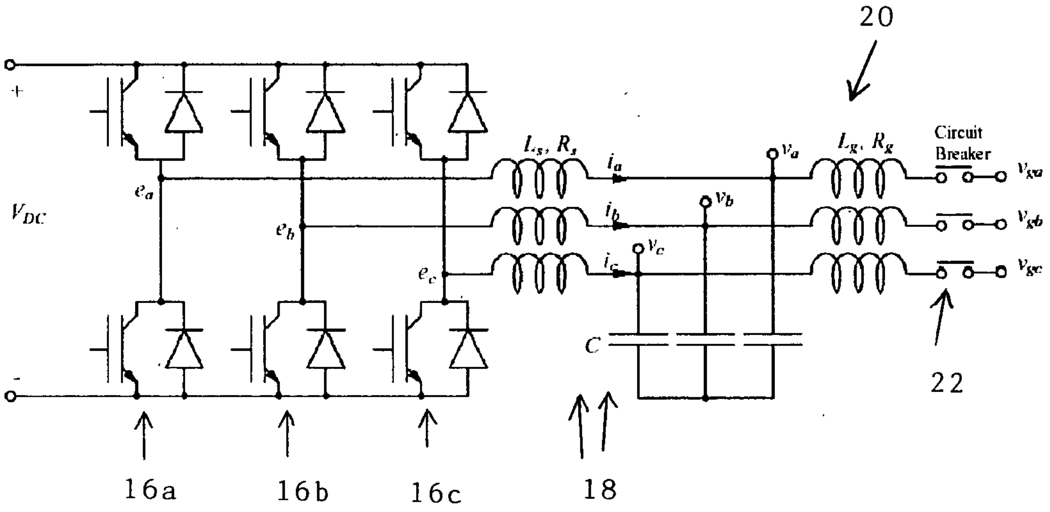

20
+
V_DC
-
e_a
e_b
e_c
L_s, R_s
i_a
i_b
i_c
v_a
v_b
v_c
C
L_g, R_g
Circuit Breaker
v_ga
v_gb
v_gc
22
16a
16b
16c
18

Figure 3

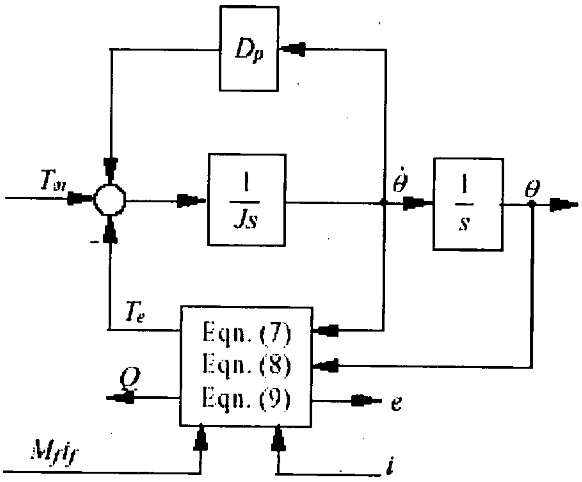
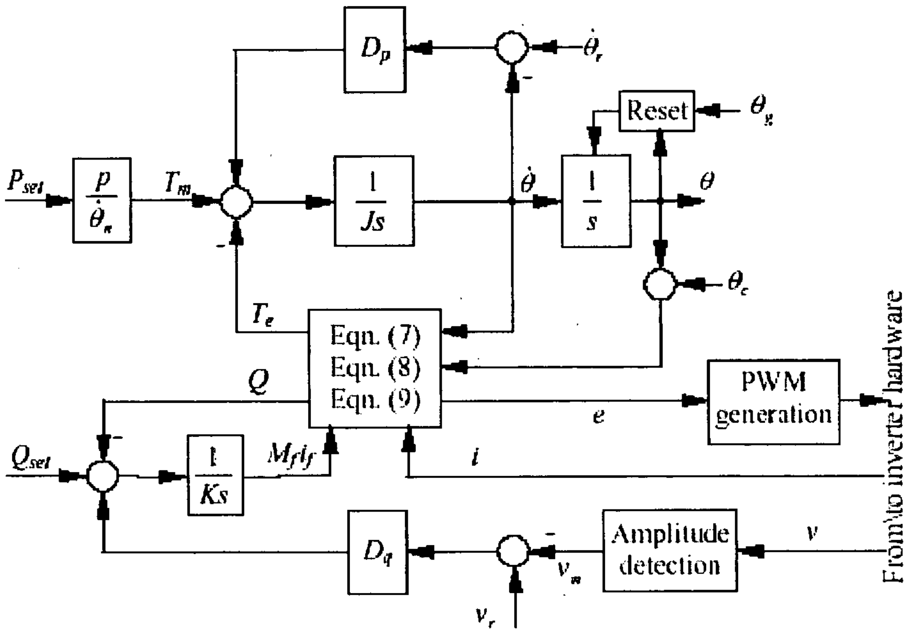
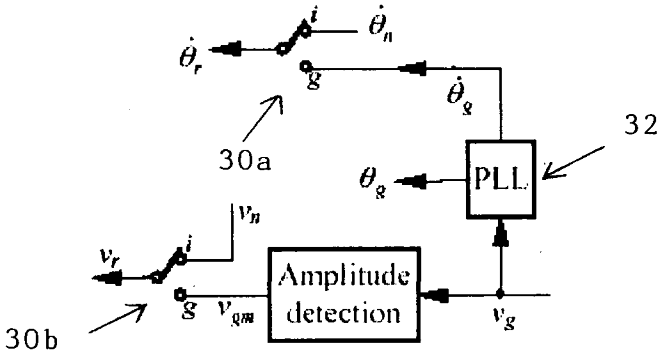

D_p
T_m
$\frac{1}{Js}$
$\dot{\theta}$
$\frac{1}{s}$
θ
-
T_e
Eqn. (7)
Eqn. (8)
Eqn. (9)
Q
e
$M_f i_f$
i

Figure 4

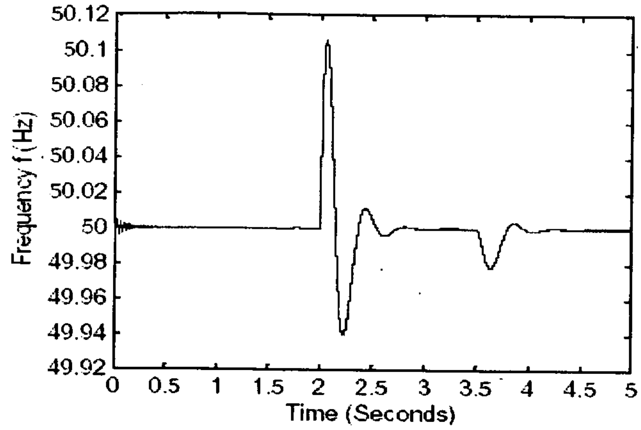


(a) Regulation of real and reactive power

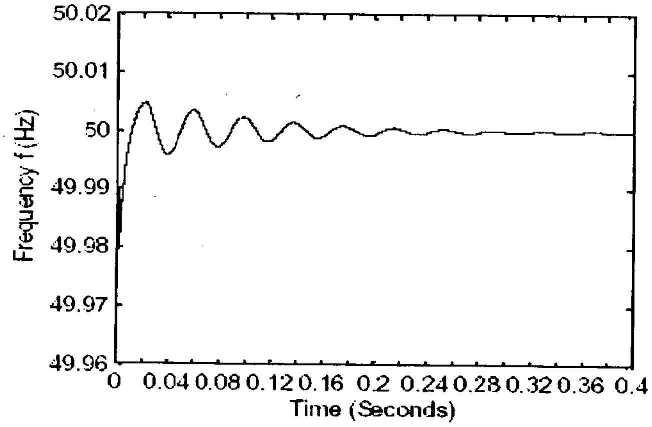


(b) Provision of references, *e.g.*, via PLL

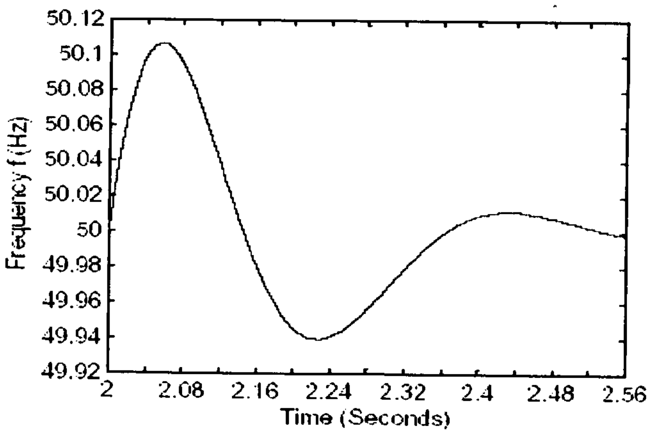
Figure 5



(a) whole period



(b) start-up



(c) after applying real power

Figure 6a

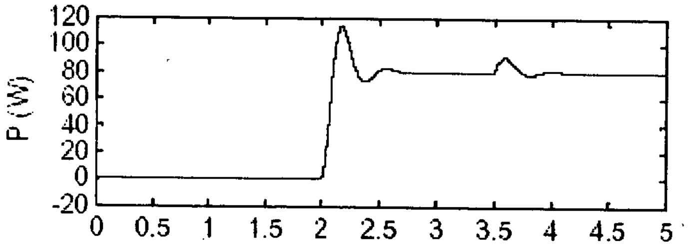


Figure 6b

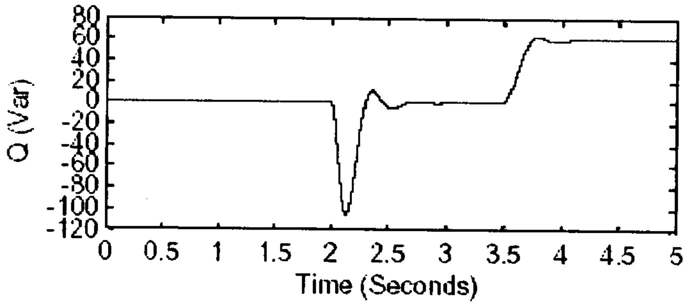
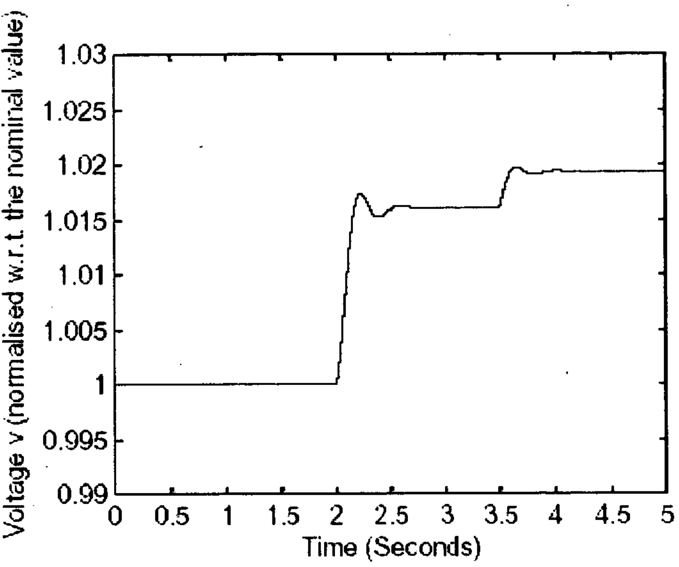
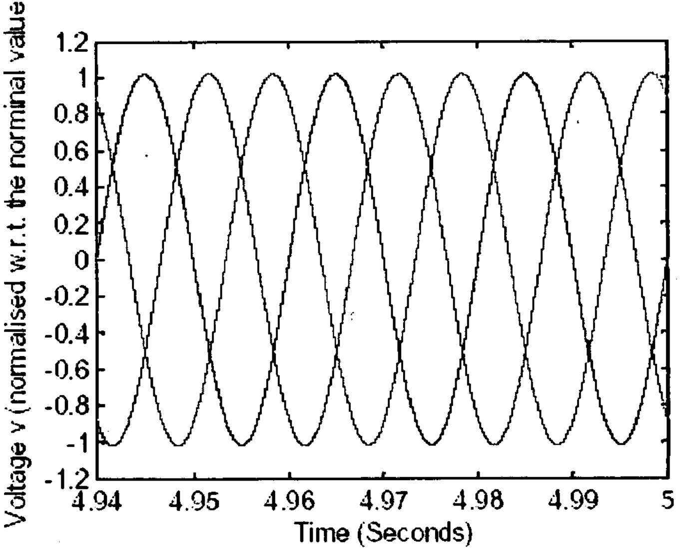


Figure 7

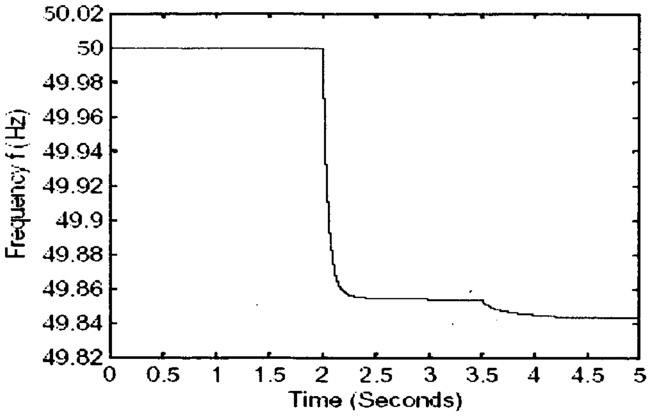


(a) the magnitude of the voltage

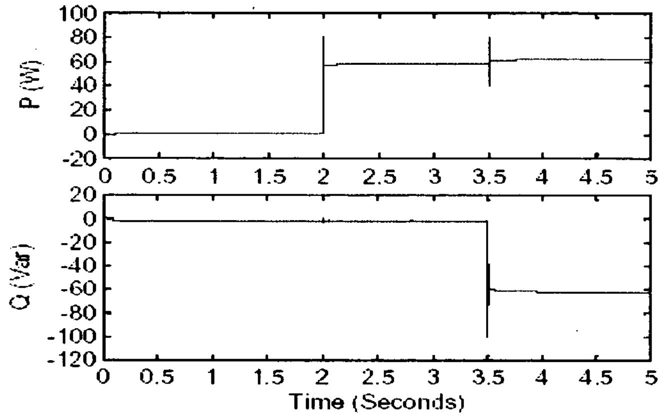


(b) at steady state

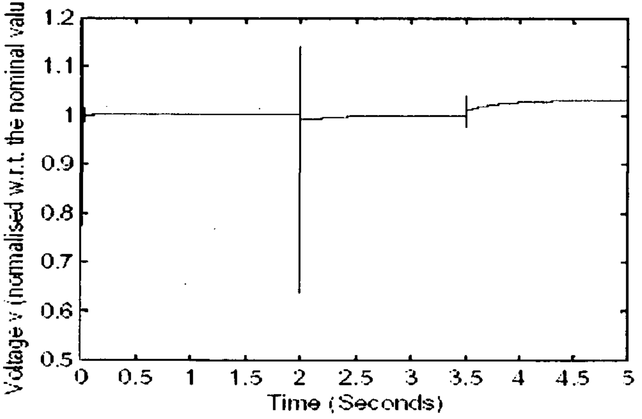
Figure 8



(a) frequency



(b) real and reactive power



(c) amplitude of the terminal voltage