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(54) Title: CONTROL OF A DOUBLY-FED INDUCTION GENERATOR

(57) Abstract: A controller for a doubly-fed induction generator, the doubly-fed induction generator comprising a stator and a rotor. The stator comprises stator terminals arranged to provide a three phase stator terminal voltage, and a three phase winding arranged to provide a stator flux described by a vector rotating at a stator frequency. The stator provides a stator electrical power supply at the stator frequency. The rotor comprises a three phase winding arranged to provide a rotor flux described by a vector rotating at substantially the stator frequency at an angular position relative to the stator flux vector. The controller is arranged to determine a control signal to cause a change substantially only in the magnitude of the rotor flux vector in response to a stator terminal voltage error signal. The controller is further arranged to determine a control signal to cause a change substantially only in the angular position of the rotor flux vector relative to the stator flux vector, in response to a stator electrical power supply error signal.
CONTROL OF A DOUBLY-FED INDUCTION GENERATOR

The present invention relates to a controller for a doubly-fed induction generator (DFIG) and to a method of controlling the same. In particular, but not exclusively, the method allows improved control of the power supply and terminal voltage of a DFIG. The method also allows the provision of support to an electricity network under fault conditions.

Conventional generating stations based upon synchronous generators are well established. A synchronous generator comprises a rotor having a winding, which is supplied with a DC rotor voltage via slip rings. This rotor voltage gives rise to a rotor flux described by a vector. The rotor rotates within a stator which comprises a three phase winding connected to an electricity network. Therefore, the stator winding has a stator flux described by a vector rotating at a stator frequency. The stator frequency is fixed by the frequency on the electricity network. The rotor is driven by a turbine at a rotational speed substantially synchronised to the rotational speed of the stator flux vector. Power is transferred from the rotor to the stator due to the interaction of the rotor and stator flux vectors.

Methods of controlling synchronous generators in order to provide efficient control over the stator terminal voltage are well known. The magnitude of the power supply output of the stator is dependent on the power output of the prime mover of the system. The prime mover is normally a steam, gas or hydraulic turbine. The angular position of the rotor flux vector relative to the stator flux vector is dependent upon the stator power supply output.

The magnitude of the stator terminal voltage of a synchronous generator can be controlled by varying the magnitude of the DC voltage supplied to the rotor. This type of control is known as Automatic Voltage Regulation and is implemented by a controller known as an Automatic Voltage Regulator (AVR). Before a generator can be connected to the UK national grid, the generator must be shown to provide a sufficient level of control in order to satisfy the “grid code” requirements for network support and operation. The grid code includes the requirement of the capability to provide voltage support and the ability to remain connected to the network following short term system faults. The most commonly considered system fault is a three
phase short circuit to ground that is quickly isolated by the opening of switchgear connected to the affected power line. AVR supplies this level of control.

Furthermore, techniques whereby synchronous generators are able to contribute to network support and operation in the event of fault conditions are known.

In many countries wind generation is becoming increasingly important, as the proportion of electricity it generates is increasing. Wind turbines operate most efficiently if they are allowed to operate at a variable rotational speed. The power extracted from the wind by a wind turbine can be maximised if the speed of the turbine is adjusted in accordance with the prevailing wind speed. However, a synchronous generator requires the rotor to be rotated at a speed substantially synchronised to the stator frequency. Therefore, a wind generator is only able to run close to its maximum efficiency over a narrow band of wind speeds. At other times fixed speed wind generators run at reduced efficiency.

An alternative form of generator known for simple wind farms is a squirrel cage induction generator. Squirrel cage induction generators are used in the simplest form of wind farms. A squirrel cage induction generator has a rotor comprising a cylinder of short circuited bars and operates at a substantially fixed rotational speed. This substantially fixed speed operation of a squirrel cage induction generator therefore does not permit the wind turbine to operate at maximum efficiency. Additionally, squirrel cage induction generators perform badly when faced with network fault conditions and usually require power factor correction equipment to satisfy operational requirements. A synchronous generator requires a controlled excitation system, unlike a squirrel cage induction generator. Therefore, due to economy and simplicity squirrel cage induction generators are used in earlier forms of wind farm in preference to synchronous generators, though neither is ideal.

One known solution is to implement a wind generator using a doubly-fed induction generator (DFIG). A DFIG comprises a rotor having a three phase winding supplied with a rotor voltage, which can be described by a vector via slip rings from a converter system. The converter system is powered by the stator terminals. As with a synchronous generator, the stator comprises a three phase winding having a stator flux described by a vector rotating at the stator frequency. The stator frequency is fixed by
the frequency of the electricity network. The converter system provides a variable frequency three phase voltage supply to the rotor. The magnitude and phase of the rotor voltage vector, with respect to the stator flux vector, can be controlled.

Under steady state conditions, the rotational speed of the rotor flux vector is equal to the rotational speed of the stator flux vector. The rotor speed (the speed of physical rotation of the rotor) can be faster or slower than the rotational speed of the stator flux vector. The difference between the rotational speed of the rotor flux vector and the rotational speed of the rotor is known as the slip speed. The slip speed is the speed at which the stator flux vector rotates relative to the rotor. Under steady state conditions the slip speed depends upon whether the rotor speed is greater than the rotational speed of the stator flux vector (super-synchronous operation) or slower (sub-synchronous operation).

Under steady state conditions, the rotor flux vector rotates synchronously with the stator flux vector, as is the case with synchronous generators. Consequently, the rotational speed of the rotor can vary, in order to maximise the output torque of the wind turbine according to the prevailing wind conditions, and hence to maximise the power developed by the wind turbine and hence the power supply of the DFIG based wind farm. The rotational speed of the rotor flux vector relative to the rotor can be controlled by varying the frequency of the rotor voltage vector.

The increasingly widespread use of wind farms equipped with DFIG generators on power networks imposes the requirement that wind farms should be able to contribute to network support and operation in the event of network faults as do the conventional generating stations based on synchronous generators. The grid code requirements for DFIGs are becoming more strict in terms of fault ride through, the ability to remain connected to the system following short term system faults, the ability to contribute to voltage support during system disturbances and the ability to contribute to system damping.

The magnitude and the angular position of the rotor voltage vector demanded of the converter system are controlled by a controller. The converter system provides the rotor with a three phase rotor voltage, which affects the magnitude and angular position of the rotor flux vector. Conventional DFIG controllers to date have concentrated on the provision of an adjustable operating speed of the rotor to
maximise turbine power output, the maintenance of the required stator terminal voltage and power supply and the control of the generator torque to match that of the wind turbine.


The rotor voltage vector is calculated in terms of direct and quadrature (d and q) components referenced to a synchronously rotating reference frame. The d axis of the frame can be arranged to coincide with the stator flux vector. The d component of the rotor voltage vector is used to exercise control over the stator terminal voltage magnitude or the power factor. The power factor defines the phase relationship between the stator terminal voltage and the stator current. The d axis rotor current error is processed to provide the demanded value of the d axis component of the rotor voltage vector. The q axis component of rotor voltage is used to exercise control over the generator torque via control over the q axis value of the rotor current. The q axis rotor current error is processed to provide the demanded value of the q axis component of the rotor voltage vector.

However, this control strategy gives rise to interaction between the control loops. Furthermore, this control strategy does not readily facilitate the provision of control characteristics that comply with the grid code requirements for DFIGs.

It is an aim of embodiments of the present invention to obviate, or mitigate, one or more of the problems associated with the prior art, whether identified herein or elsewhere. Specifically, it is an aim of embodiments of the present invention to provide a DFIG controller that provides substantially independent control of the stator terminal voltage and the stator electrical power supply via control of the magnitude and the angular position of the rotor flux vector. Furthermore, it is an aim of embodiments of the present invention to provide a DFIG controller with operational and control compatibility with conventional power stations and with the ability to contribute to network support and operation as required by the grid code. This can include one or more of the ability to contribute to voltage support and recovery
following network faults, a positive contribution to overall network damping and the provision of short term frequency support to the network in the event of loss of network generation.

According to a first aspect, the present invention provides a controller for a doubly-fed induction generator, the doubly-fed induction generator comprising: a stator comprising stator terminals arranged to provide a three phase stator terminal voltage supply, and a three phase winding arranged to provide a stator flux described by a vector rotating at a stator frequency, and arranged to provide a stator electrical power supply at the stator frequency; and a rotor comprising a three phase winding arranged to provide a rotor flux described by a vector rotating at substantially the stator frequency at an angular position relative to the stator flux vector; wherein the controller is arranged to determine a control signal to cause a change substantially only in the magnitude of the rotor flux vector in response to a stator terminal voltage error signal, and to determine a control signal to cause a change substantially only in the angular position of the rotor flux vector relative to the stator flux vector, in response to a stator electrical power supply error signal.

By providing independent control of the magnitude and the angular position of the rotor flux vector, substantially independent control over the stator terminal voltage vector and the power supply can thus be achieved. This independent control allows a DFIG controller to emulate the control of a controller for a synchronous generator. The control of the stator terminal voltage is similar to that provided by an Automatic Voltage Regulator (AVR) for a synchronous generator. The control of the stator electrical power supply output from the DFIG provides the ability to maintain the generator power (or torque) at a value that matches that of a wind turbine driving the generator. Such a controller allows the provision of a DFIG satisfying the grid code requirements for fault ride through. This enables DFIGs to contribute to network operation by providing voltage support and recovery following network faults.

Preferably, the stator terminal voltage error signal is indicative of the difference between the magnitude of the stator terminal voltage and the magnitude of a predetermined stator terminal voltage reference signal. Preferably, the stator electrical power supply error signal is indicative of the difference between the stator
electrical power supply and a predetermined stator electrical power supply reference signal.

The stator electrical power supply may be indicative of a torque exerted by the rotor.

Preferably, the control signals are indicative of a desired rotor voltage described by a vector, for supply to the rotor three phase winding.

The controller may be arranged to output said control signals in polar coordinate form, with respect to a reference frame rotating at stator frequency. Alternatively, the controller can be arranged to output said control signals in rectangular coordinate form, with respect to a reference frame rotating at stator frequency.

The controller may be arranged to determine said control signals by comparing a rotor flux vector magnitude reference value and a value indicative of the actual magnitude of the rotor flux vector and comparing a rotor flux vector angular position reference value and a value indicative of the actual angular position of the rotor flux vector relative to the stator flux vector.

The controller may comprise a first compensator arranged to receive the stator terminal voltage error signal and determine a rotor flux vector magnitude reference value. The first compensator comprises a proportional plus integral controller and a phase compensation element.

The controller may comprise a second compensator arranged to receive the stator electrical power supply error signal and determine a rotor flux vector angular position reference value relative to the stator flux vector angular position. The second compensator may comprise a proportional plus integral controller and a phase compensation element.

The controller may further comprise at least one auxiliary controller, each auxiliary controller being arranged to determine an auxiliary control signal in response to at least one of a rotor speed signal, a stator electrical power supply signal, a slip signal and a stator frequency signal, the controller being arranged to utilise the auxiliary control signal to modify the value of a signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector.
A first auxiliary controller may be arranged to determine a first auxiliary control signal from a first auxiliary input signal comprising at least one of the rotor speed signal and the slip signal, the first auxiliary controller comprising a washout filter, an integrator, a compensator and an output value limiter.

A second auxiliary controller may be arranged to determine a second auxiliary control signal from a second auxiliary input signal comprising at least one of the rotor speed signal, the stator electrical power supply signal, the slip signal and the signal indicative of the stator frequency, the second auxiliary controller comprising a washout filter, a compensator, an amplifier and an output value limiter.

A third auxiliary controller may be arranged to determine a third auxiliary control signal from the stator frequency signal and at least one of the rotor speed signal and the slip signal, the third auxiliary controller being arranged to: determine a first resultant signal by washout filtering, first compensating, output value limiting and second compensating the stator frequency signal; determine a second resultant signal by washout filtering at least one of the rotor speed signal and the slip signal; determine an auxiliary error signal from the difference between the resultant signals; and determine the third auxiliary control signal by third compensating the auxiliary error signal.

Preferably, the controller is arranged to selectively inhibit the operation of the first auxiliary controller, when the third auxiliary controller operates.

The signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector may comprise the rotor flux vector angular position reference value, the controller being arranged to utilise at least one of the auxiliary control signals to modify the rotor flux vector angular position reference value relative to the stator flux vector angular position.

The signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector may comprise the predetermined stator electrical power supply reference signal, the controller being arranged to utilise at least one of the auxiliary control signals to modify the predetermined stator electrical power supply reference signal.

The signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector may comprise an angular position of the desired rotor
voltage vector, the controller being arranged to utilise at least one of the auxiliary control signals to modify the angular position of the desired rotor voltage vector.

According to a second aspect, the present invention provides a doubly-fed induction generator comprising a controller as described above.

According to a third aspect, the present invention provides a method of controlling a doubly-fed induction generator, the doubly-fed induction generator comprising: a stator comprising stator terminals arranged to provide a three phase stator terminal voltage supply, and a three phase winding arranged to provide a stator flux described by a vector rotating at a stator frequency and arranged to provide a stator electrical power supply at the stator frequency; and a rotor comprising a three phase winding arranged to provide a rotor flux described by a vector rotating at substantially the stator frequency at an angular position relative to the stator flux vector; the method comprising: determining a control signal to cause a change substantially only in the magnitude of the rotor flux vector in response to a stator terminal voltage error signal; and determining a control signal to cause a change substantially only in the angular position of the rotor flux vector relative to the stator flux vector, in response to a stator electrical power supply error signal.

According to a fourth aspect, the present invention provides a controller for a doubly-fed induction generator, the doubly-fed induction generator comprising: a stator comprising a three phase winding arranged to provide a stator flux described by a vector rotating at a stator frequency and arranged to provide a stator electrical power supply at the stator frequency; and a rotor comprising a three phase winding arranged to provide a rotor flux described by a vector rotating at substantially the stator frequency at an angular position relative to the stator flux vector; wherein the controller comprises at least one auxiliary controller, each auxiliary controller being arranged to determine an auxiliary control signal in response to at least one of a rotor speed signal, a slip signal, a stator frequency signal and a stator electrical power supply signal, the controller being arranged to utilise the auxiliary control signal to modify the value of a signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector.

A first auxiliary controller may be arranged to determine a first auxiliary control signal from a first auxiliary input signal comprising at least one of the rotor
speed signal and the slip signal, the first auxiliary controller comprising a washout filter, an integrator, a compensator and an output value limiter.

A second auxiliary controller may be arranged to determine a second auxiliary control signal from a second auxiliary input signal comprising at least one of the rotor speed signal, the stator electrical power supply signal, the slip signal and the stator frequency signal, the second auxiliary controller comprising a washout filter, a compensator, an amplifier and an output value limiter.

A third auxiliary controller may be arranged to determine a third auxiliary control signal from the stator frequency signal and at least one of the rotor speed signal and the slip signal, the third auxiliary controller being arranged to: determine a first resultant signal by washout filtering, first compensating, output value limiting and second compensating the stator frequency; determine a second resultant signal by washout filtering at least one of the rotor speed signal and the slip signal; determine an auxiliary error signal from the difference between the resultant signals; and determine the third auxiliary control signal by third compensating the auxiliary error signal.

Preferably, the controller is arranged to selectively inhibit the operation of the first auxiliary controller.

The controller may be arranged to determine a control signal to cause a change substantially only in the stator electrical power supply, in response to a stator electrical power supply error signal indicative of the difference between the stator electrical power supply and a predetermined stator electrical power supply reference signal, and the signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector may comprise the predetermined stator electrical power supply reference signal and the controller may be arranged to utilise at least one of the auxiliary control signals to modify the predetermined stator electrical power supply reference signal.

The signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector may comprise a signal indicative of a desired rotor voltage described by a vector, for supply to the rotor three phase winding, and the controller may be arranged to utilise at least one of the auxiliary control signals to modify the angular position of the desired rotor voltage vector.
According to a fifth aspect, the present invention provides a doubly-fed induction generator comprising a controller as described above.

According to a sixth aspect, the present invention provides a method of controlling a doubly-fed induction generator, the doubly-fed induction generator comprising: a stator comprising a three phase winding arranged to provide a stator flux described by a vector rotating at a stator frequency and arranged to provide a stator electrical power supply at the stator frequency; and a rotor comprising a three phase winding arranged to provide a rotor flux described by a vector rotating at substantially the stator frequency at an angular position relative to the stator flux vector; the method comprising: determining an auxiliary control signal in response to at least one of a rotor speed signal, a slip signal, a stator frequency signal and the stator electrical power supply signal; and utilising the auxiliary control signal to modify the value of a signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector.

According to a seventh aspect, the present invention provides a data carrier carrying computer program code means to cause a computer to carry out a method as described above.

According to an eighth aspect, the present invention provides a computer apparatus comprising: a program memory containing processor readable instructions; and a processor for reading and executing the instructions contained in the program memory; wherein said processor readable instructions comprise instructions controlling the processor to carry out a method as described above.

A further advantage of embodiments of the present invention is that the dynamic characteristic of the DFIG presented to the network can be made to resemble that of a synchronous generator.

A further advantage of embodiments of the present invention is that a DFIG generator can act as a power system stabiliser, and therefore provide damping to the network.

A further advantage of embodiments of the present invention is that in the event of the disconnection of a generator on the network a DFIG controller can provide a short term increase in power supply in order to provide frequency support.
Further advantages of embodiments of the present invention will become readily apparent from the following description.

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

Figure 1 schematically illustrates a DFIG in combination with a controller in accordance with an embodiment of the present invention;

Figure 2 illustrates a vector diagram representation of the operation of a synchronous generator;

Figure 3 illustrates a vector diagram representation of the operation of a DFIG;

Figure 4 schematically illustrates a controller for a DFIG in accordance with an embodiment of the present invention;

Figure 5 schematically illustrates a first optional part of the controller for a DFIG of Figure 4;

Figure 6 schematically illustrates a second optional part of the controller for a DFIG of Figure 4;

Figure 7 schematically illustrates a controller for a DFIG in accordance with a further embodiment of the present invention;

Figure 8 schematically illustrates a first auxiliary controller in accordance with embodiments of the present invention;

Figure 9 schematically illustrates a second auxiliary controller in accordance with embodiments of the present invention;

Figure 10 schematically illustrates a third auxiliary controller in accordance with embodiments of the present invention;

Figure 11 schematically illustrates a controller for a DFIG in accordance with a further embodiment of the present invention;

Figure 12 schematically illustrates a controller for a DFIG in accordance with an additional embodiment of the present invention;

Figure 13 schematically illustrates a controller for a DFIG in accordance with a further embodiment of the present invention;

Figure 14 schematically illustrates a controller for a DFIG in accordance with an additional embodiment of the present invention; and
Figure 15 schematically illustrates a controller for a DFIG in accordance with a further embodiment of the present invention.

Throughout the description identical reference numerals are used to refer to similar features.

Referring first to Figure 1 this illustrates a DFIG 1 controlled by a controller 2 in accordance with an embodiment of the present invention. The DFIG comprises a rotor 3, having a three phase winding 4, and a stator 5 having a three phase winding 6. The rotor 3 rotates within the stator 5, and is driven by a wind turbine 7.

Stator 5 has three phase voltage terminals 8 which supply a stator terminal voltage $V_s$ and an electrical power supply $P_e$ to transformer 9. Transformer 9 steps up the stator terminal voltage $V_s$ to a suitable level for provision to the network 10.

The stator three phase winding 6 provides a stator flux described by a vector $\Psi_s$, which rotates at a stator frequency $\omega_s$, fixed by the network frequency. A vector has a magnitude value and an angular position value.

DFIG 1 further comprises a converter system 11. Converter system 11 comprises first and second converters 12 and 13. First converter 12 has a three phase voltage input supplied by the stator terminals 8 and converts this to a DC voltage. First converter 12 is fed from the stator terminals 8 via a reactive link. First converter 12 supplies the DC voltage to second converter 13 via DC bus 14. DC bus 14 is bridged by capacitor 15 to substantially remove any AC voltage component. Second converter 13 converts the DC voltage to a rotor voltage described by a vector $V_r$. The rotor voltage is supplied to the three phase winding 4 on the rotor 3 via slip rings. The magnitude and phase of the rotor voltage vector $V_r$ are controllable. Controller 2 determines a control signal $V_{rdem}$ (desired rotor voltage vector) that is supplied to the second converter 13 to adjust $V_r$.

Converter system 11 permits the two way transfer of power between the rotor 3 and the stator 5 connection to transformer 9. At super-synchronous speeds (the rotor 3 rotating faster than the stator flux vector $\Psi_s$) the converter system 11 transfers power from the rotor 3 to the stator terminals 8. At sub-synchronous speeds (the rotor 3 rotating slower than the stator flux vector $\Psi_s$) the rotor 3 absorbs power via the converter system 11 from the stator terminals 8.
The rotor voltage vector $V_r$ is controlled such that under steady state conditions the combined speed of the rotor $3 \omega_r$ plus the rotational speed of the rotor flux vector $\Psi_r$ relative to the rotor (known as the slip speed $s$) matches that of the synchronously rotating stator flux vector $\omega_s$, which is fixed by the network frequency. Under steady state conditions slip speed $s$ can be calculated as $s = \omega_s - \omega_r$. The actual rotational speed of the rotor flux vector is $\omega_r + s$. The speed of the rotor $3$ is dictated by the wind turbine $7$ and is adjusted to maximise the turbine power output at the prevailing wind speed. Manipulation of the frequency of the rotor voltage vector $V_r$, supplied to the rotor by the converter system, by the controller $2$ permits the DFIG turbine to be operated to make the most efficient use of the available wind power.

The controller $2$, in accordance with embodiments of the present invention can utilise a number of input signals derived from the DFIG $1$ in order to control the desired rotor voltage vector $V_{rdem}$. These can include one or more of the stator electrical power supply $P_e$ supplied by the stator $5$, the three phase values of the stator terminal voltage $V_s$, the stator current $I_{ls}$, the rotor current $I_r$, the stator frequency $\omega_s$, the slip speed $s$ and the rotor speed $\omega_r$. If the stator terminal voltage $V_s$ and the stator current $I_{ls}$ are included as input signals, then other signals, for instance the stator electrical power supply $P_e$, may be calculated, rather than require further inputs.

The controller $2$ exercises independent control over the stator terminal voltage $V_s$ and the stator electrical output power supply $P_e$ by independently controlling the magnitude and angular position respectively of the rotor flux vector $\Psi_r$. Control over the rotor flux vector $\Psi_r$ can be achieved by controlling the desired rotor voltage vector $V_{rdem}$. In order to calculate the desired values of the magnitude and the angular position of the rotor flux vector $\Psi_r$, predetermined values for the desired values of the stator terminal voltage $V_{\text{ref}}$ and the power supply $P_{\text{ref}}$ are input to the controller $2$. The desired value for the stator output power supply $P_{\text{ref}}$ can be calculated from the slip speed $s$ by power controller $16$.

It is desirable that the stator terminal voltage and transient variations in the stator electrical power supply of a DFIG are separately controllable. A DFIG controlled according to embodiments of the present invention satisfies the grid code requirements for fault ride through. Additionally, it is desirable that a DFIG provides the same level, or better, of network support and operation as provided by
synchronous generators. If this capability is not provided then the operational characteristics of the network will vary widely as the proportion of synchronous generators and DFIGs varies. This would present severe difficulties to the network operator in providing the required level of stability and security. Using conventional DFIG controllers such as the one described in the paper by Ekanayake et al whilst it is possible to provide control over the stator terminal voltage and the electrical power supply an undesirable level of interaction exists between the two.

A convenient method of representing a generator for the purposes of analysis, simulation and control is in terms of a synchronously rotating reference frame having direct and quadrature axes (d and q axes), with the q axis chosen to align with one of the vector quantities within the generator.

The controller 2 utilises a control strategy that aims to emulate the control action of a conventional synchronous generator. A vector diagram representation of the operating conditions of such a conventional round rotor synchronous generator is illustrated in Figure 2. In this diagram \( E_g \) represents an internally generated voltage within the stator. The q axis is chosen to align with the internally generated voltage \( E_g \). The internally generated voltage \( E_g \) rotates synchronously at the stator frequency \( \omega_s \). Therefore, all other rotating vectors can be described in terms of their magnitude and angular position relative to the internally generated voltage \( E_g \) within the same reference frame.

The magnitude of the internally generated voltage \( E_g \) is determined by a rotor flux vector \( \Psi_{fd} \), with the internally generated voltage \( E_g \) being 90\(^\circ\) out of phase with the rotor flux vector \( \Psi_{fd} \). Therefore the rotor flux vector \( \Psi_{fd} \) is aligned with the d axis of the reference frame. The physical position of the field winding of the rotor with respect to a rotating stator terminal voltage vector \( E_s \) defines the position of the rotor flux vector \( \Psi_{fd} \) and is aligned with the d axis of the chosen synchronously rotating reference frame. In per unit terms the internally generated voltage \( E_g \) has the same magnitude as the field voltage \( E_{fb} \), which is the DC voltage, supplied to the rotor.

The magnitude of the stator terminal voltage vector \( E_s \) is dependent upon the magnitude of the internally generated voltage \( E_g \). The difference between the two vectors, assuming negligible stator resistance, can be calculated from the stator current vector \( I_s \), as \( jX_s I_s \), where \( X_s \) is the synchronous reactance of the generator.
Therefore the stator terminal voltage vector $V_s$ can be controlled by controlling the magnitude of the field voltage $E_{fd}$ supplied to the rotor.

The rotor angle $\delta_r$ is defined as the angle between the internally generated voltage $E_{ig}$ and the stator terminal voltage vector $E_s$. For a given field voltage $E_{fd}$ and stator terminal voltage vector $E_s$, the rotor angle $\delta_r$ is determined by the output power of the generator.

With a conventional synchronous generator, control can be exercised only over the field voltage magnitude, so that independent control of the stator terminal voltage vector $E_s$ and transient variations in the stator electrical power supply is not possible. Whilst the magnitude of the rotor flux vector can be adjusted by the excitation control scheme, the position of the rotor flux vector is fixed by the physical position of the rotor itself.

Figure 3 illustrates an equivalent vector diagram representation of the operating conditions of a DFIG. In this case $E_{ig}$ represents the internally generated voltage vector in the stator (often referred to as the voltage behind the transient reactance). The magnitude of the internally generated voltage vector $E_{ig}$ depends on the magnitude of the rotor flux vector $\Psi_r$. The rotor flux vector $\Psi_r$ is dependent upon the generator stator and rotor currents, but can be manipulated by adjustment of the rotor voltage vector $V_r$.

The magnitude of the stator terminal voltage vector $V_s$ is dependent upon the magnitude of the internally generated voltage $E_{ig}$. Assuming negligible stator resistance, the difference between the two vectors can be calculated from the stator current vector $I_{is}$, as $jX' I_{is}$, where $X'$ is the transient reactance of the generator. The transient reactance $X'$ can be calculated from the stator self inductance $L_{ss}$, the mutual inductance between the stator and the rotor $L_m$ and the rotor self inductance $L_{rr}$ as follows:

$$X' = \left( L_{ss} - \frac{L_m^2}{L_{rr}} \right) \omega_s$$

when transient reactance $X'$ and the inductances $L_{ss}$, $L_{rr}$ and $L_m$ are expressed in per unit terms, i.e. frequency $\omega_s = 1$ in per unit terms.

Therefore, the stator terminal voltage vector $V_s$ can be controlled by controlling the magnitude of the rotor voltage vector $V_r$ supplied to the rotor.
For a DFIG, a synchronously rotating reference frame is normally defined with the q axis chosen to align with the stator terminal voltage vector $V_s$. The stator terminal voltage vector $V_s$ rotates synchronously with a stator flux vector $\Psi_s$. For a given rotor voltage vector $V_r$ and stator terminal voltage vector $V_s$, a pseudo rotor angle $\delta_{ig}$ exists between the internally generated voltage vector $E_{ig}$ and the stator terminal voltage vector $V_s$. The pseudo rotor angle $\delta_{ig}$ is determined by the output power supply $P_e$ of the generator. The term pseudo rotor angle $\delta_{ig}$ refers to the fact that the physical position of the rotor can be varying with respect to the synchronously rotating reference frame. However, with the addition of the appropriate variable frequency rotor voltage vector $V_r$, the internally generated voltage vector $E_{ig}$ can be held at a desired angular position with respect to the stator terminal voltage vector $V_s$.

As the internally generated voltage vector $E_{ig}$ is orthogonal to the rotor flux vector $\Psi_r$, the angle between the rotor flux vector $\Psi_r$ and the d axis of the reference frame is also given by $\delta_{ig}$.

It can be seen from this, therefore, that independent control of the stator terminal voltage $V_s$ and transient variations in the stator electrical power supply $P_e$ of a DFIG can be achieved by independent control of the magnitude and the angular position respectively of the internally generated voltage $E_{ig}$. As in per unit terms the internally generated voltage $E_{ig}$ is directly related to the rotor flux vector $\Psi_r$ ($E_{ig} = j\Psi_r(L_m/L_m)$) then it is also true that this independent control can be achieved by independent control of the magnitude and the angular position respectively of the rotor flux vector $\Psi_r$.

A controller and a method are described for generating a control signal to cause a change substantially only in the magnitude of the rotor flux vector in response to a stator terminal voltage error signal, and to determine a control signal to cause a change substantially only in the angular position of the rotor flux vector relative to the stator flux vector, in response to a power supply error signal.

Consequently, the controller is able to emulate the control of a synchronous generator with respect to the control over the magnitude of the rotor flux. Furthermore, by exercising transient control over the angular position of the rotor flux vector with respect to the stator flux vector, control over transient power variations is enabled. For a synchronous generator, such control over the angular position of the
rotor flux vector and hence the transient power variations of the stator electrical power supply could only be achieved through refined turbine governor control of a form not currently available. Consequently, embodiments of the present invention offer a control capability beyond the scope of a conventional synchronous generator.

Disturbances on the network result in changes in the load currents of the connected generators. In the case of synchronous generators these produce changes in the stator terminal voltage $E_s$ that are counteracted by an AVR supplying feedback to vary the DC field voltage $E_{fd}$ supplied to the rotor coil. Changes in the generator power supply (or torque) are produced that cause oscillatory variations in rotor speed and rotor angle. As an increase in the rotor angle between the internally generated voltage $E_{ig}$ and the stator terminal voltage vector $E_s$ causes an increase in the power output there is a natural feedback system to control the power supply of the generator.

Due to the asynchronous operation of a DFIG the rotor flux vector $\Psi_r$ does not directly correspond to a physical position on the rotor. Therefore, the natural dynamic response characteristic of a DFIG to system disturbances is distinctly different from that of a synchronous generator. The preferred embodiment of the present invention provides a means of controlling the magnitude and the angular position (with respect to the stator flux vector $\Psi_s$) of the rotor flux vector $\Psi_r$ (or equivalently the magnitude and the angular position of the internally generated voltage $E_{ig}$).

Figure 4 illustrates a controller 20 for a DFIG in accordance with an embodiment of the present invention. The controller 20 comprises two distinct control loops. In the first loop 21 the controller 20 calculates a stator terminal voltage error signal $V_{ser}$ equal to the difference between the magnitude of the stator terminal voltage $V_s$ and a predetermined stator terminal voltage reference signal $V_{sref}$ at a first summing junction 22.

The stator terminal voltage error signal $V_{ser}$ is processed by a first compensator 23. The first compensator 23 comprises a proportional plus integral controller and a phase compensation element. The phase compensation is in order to ensure suitable margins of loop stability. The output is a rotor flux vector magnitude reference value $\Psi_{r\text{magref}}$. 
In the second loop 25 the controller calculates a power supply error signal $P_{err}$ equal to the difference between the power supply $P_s$ and a predetermined power supply reference signal $P_{ref}$ at a second summing junction 26.

The power supply error signal $P_{err}$ is processed by a second compensator 27. The second compensator 27 comprises a proportional plus integral controller and a phase compensation element. The phase compensation is in order to ensure suitable margins of loop stability. The output is a rotor flux vector angular position reference value $\Psi_{r, \text{mag ref}}$, relative to the stator flux vector $\Psi_s$.

The magnitude and angular position reference values of the rotor flux vector, $\Psi_{r, \text{mag ref}}$ and $\Psi_{r, \text{ang ref}}$, are passed to a sub-controller 29. Sub-controller 29 compares the reference values and actual values of the magnitude and angular position of the rotor flux vector, $\Psi_{r, \text{mag}}$ and $\Psi_{r, \text{ang}}$. The resultant error signals are passed through appropriate control elements to derive a control signal equal to the desired rotor voltage vector $V_{r, \text{dem}}$. The desired rotor voltage vector $V_{r, \text{dem}}$ can be passed to the second converter 13 in either polar coordinate or rectangular coordinate form in order for the converter to generate the rotor voltage vector to supply to the three phase winding 4 on the rotor 3.

The actual value of the rotor flux vector $\Psi_r$ can be obtained from measured values of the stator current $I_s$ and the rotor current $I_{sr}$ together with known quantities for the rotor self inductance $L_r$ and the mutual inductance between the rotor and the stator $L_m$ as follows:

$$\Psi_r = L_r I_{sr} - L_m I_s$$

If the controller is based upon control of the internally generated voltage $E_{ig}$ then this can be calculated from the stator current $I_s$ and the stator terminal voltage vector $V_s$ as follows:

$$E_{ig} = V_s + Z_s I_s$$

where $Z_s$ is the stator impedance. $Z_s$ can be calculated from the stator resistance $R_s$ and the transient reactance $X'$ as follows:

$$Z_s = R_s + jX'$$

Sub-controller 29 can take one of two forms illustrated respectively in Figures 5 and 6. Referring to Figure 5 sub-controller 29 comprises two control loops 40 and 41. In control loop 40, sub-controller 29 calculates a rotor flux vector magnitude
error signal $\Psi_{\text{magerr}}$ from the difference between the actual value of the magnitude of the rotor flux vector $\Psi_{\text{mag}}$ and the rotor flux vector magnitude reference value $\Psi_{\text{magref}}$.

The rotor flux vector magnitude error signal $\Psi_{\text{magerr}}$ is processed by a proportional plus integral controller 42 and a compensator 43 to ensure adequate margins of loop stability and an output value limiter 47 to produce the desired magnitude of the rotor voltage vector $V_{\text{magdem}}$.

In control loop 41, sub-controller 29 calculates a rotor flux vector angular position error signal $\Psi_{\text{angerr}}$ from the difference between the actual value of the angular position of the rotor flux vector $\Psi_{\text{ang}}$ and the desired value of the rotor flux vector angular position reference value $\Psi_{\text{angref}}$.

The rotor flux vector angular position error signal $\Psi_{\text{angerr}}$ is processed by a proportional plus integral controller 44 and a compensator 45 to ensure adequate margins of loop stability and an output value limiter 48 to produce the desired angular position of the rotor voltage vector $V_{\text{angdem}}$.

Depending on the form of input accepted by the converter 13, the desired rotor voltage vector $V_r$ can be defined in terms of polar coordinates $V_{\text{magdem}}$ and $V_{\text{angdem}}$ or in terms of rectangular coordinates $V_{\text{rddem}}$ and $V_{\text{rdqdem}}$ by passing the coordinates $V_{\text{magdem}}$ and $V_{\text{angdem}}$ through a polar to rectangular coordinate converter 46.

Figure 6 illustrates an alternative form of the sub controller 29. In this form the rotor flux vector reference value $\Psi_r$ is firstly converted from polar coordinates to rectangular coordinates by polar to rectangular coordinate converter 50. These rectangular coordinates are then compared with the actual values of the rotor flux vector $\Psi_r$ to calculate a rotor flux vector error signal $\Psi_{\text{err}}$ in rectangular coordinate form. As before, these error signals are processed by proportional plus integral controllers 51 and 52, compensators 53 and 54 and output value limiters 56 and 57 to calculate the desired values of the rectangular coordinates of the rotor voltage vector $V_{\text{rddem}}$ and $V_{\text{rdqdem}}$. Optionally this may be converted back to polar coordinate form by passing the desired value of the rotor voltage vector $V_r$ through a rectangular to polar coordinate converter 55.

Simulation of a controller in accordance with the above embodiment of the present invention has shown that when a three phase fault occurs close to the transformer of a DFIG controlled in this way the stator terminal voltage $V_s$ recovers
more quickly on fault clearance than is the case for conventional DFIG controllers. The power supply $P_e$ is also more quickly re-established. Voltage and power transients are less oscillatory than is the case with a synchronous generator.

Furthermore, the transient performance of synchronous generators on the network is also improved over that experienced by a network comprising only synchronous generators. Thus, the DFIG controller provides a more stable and better damped dynamic performance than that achieved by a conventional synchronous generator with AVR control.

Such a controlled DFIG is also capable of withstanding longer duration faults than is the case with synchronous generators, before full loss of synchronisation with the network is lost.

Referring now to Figure 7 this illustrates a controller 60 for a DFIG in accordance with a further embodiment of the present invention. In this embodiment the basic controller as illustrated in Figure 4 is enhanced by one or more optional auxiliary controllers 61, 62, 63. As such, the same reference numerals are used to refer to components similar in both figures. Each of the auxiliary controllers generates an auxiliary control signal $U_{\text{aux1}}$, $U_{\text{aux2}}$, $U_{\text{aux3}}$. The auxiliary control signals are combined at summing junction 64. The auxiliary control signals are used to modify a signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector. In Figure 7 this is achieved by adding the combined auxiliary control signals to the rotor flux vector angular position reference value $\Psi_{\text{rangen}}$ at summing junction 65.

The incorporation of the auxiliary controllers allows the rotor flux vector angular position reference value $\Psi_{\text{rangen}}$ to be manipulated, and thus allows additional control over the actual position of the rotor flux vector angular position $\Psi_{\text{rang}}$. In this manner, and dependent upon the construction of each auxiliary controller and how they are used in combination, the dynamic response of the DFIG can be modified. The synchronising power characteristics of a synchronous generator can be emulated. Additionally, the DFIG can make a contribution to network damping and a contribution to frequency regulation in the event of a loss of power generation on the network.
Each one of the auxiliary controllers 61, 62, 63 provides an auxiliary control signal $U_{aux1}$, $U_{aux2}$, $U_{aux3}$ in response to at least one of a rotor speed signal $\omega_r$, a slip signal $s$, the stator frequency $\omega_s$ and the power supply $P_e$.

Referring now to Figure 8, this illustrates the arrangement of the first auxiliary controller 61. First auxiliary controller 1 allows the DFIG to emulate the synchronising power (or torque) characteristics of a synchronous generator.

For a synchronous generator, when disturbances on the network cause variations in the generator power output (and therefore load torque) there is a natural stabilising mechanism. Any resulting fall in torque below the level of the turbine torque gives rise to an acceleration of the rotor and an increase in the rotor speed and angular position of the rotor flux vector. Since an increase in rotor angle causes an increase in the generator torque, the generator torque is driven back towards a level that matches the turbine torque. The restoring torque is often referred to as a “synchronising torque” and the associated power as the “synchronising power”. This exercises a stabilising influence over the generator and helps synchronous the generator with the other generators on the network.

For a DFIG, disturbances in the generator load also result in variations in the speed and angular position of the rotor. However, due to the asynchronous operation of a DFIG (the physical position of the rotor not necessarily being synchronised with the rotation of the stator flux vector $\Psi_s$) the position of the rotor flux vector $\Psi_r$ is not dependent on the physical position of the rotor. Therefore, “synchronising torque” is not developed.

First auxiliary controller 61 generates a “pseudo rotor angle” signal $U_{aux1}$ by integrating over time the rotor speed variation of the DFIG. This can be used to adjust the rotor flux vector angular position reference value $\Psi_{rangef}$. Manipulation of the actual rotor flux vector angular position $\Psi_{rang}$ produces variations in the stator power $P_e$ and torque $T_e$, which result in the stator power $P_e$ and torque $T_e$ oscillations equivalent to those of a synchronous generator during a network transient condition.

One method of generating the “pseudo rotor angle” signal $U_{aux1}$ as shown in Figure 8 is by passing either the rotor speed $\omega_r$ or slip $s$ signal through a washout filter 70 to remove any steady state component. The signal output from the washout filter is then integrated over time by integrator 71 and compensated in compensator 72.
The term "compensator" used herein is to be interpreted broadly as comprising phase and / or amplitude compensation. If a compensator is arranged to provide only phase compensation, an amplifier may also be provided. Compensator 72 provides the “pseudo rotor angle” signal at an appropriate magnitude, lagging the rotor speed variations by substantially 90° at the system oscillation frequency. The “pseudo rotor angle” signal is then passed through an output value limiter 73. The output limiter ensures that the value of the first auxiliary control signal does not go beyond predetermined threshold values.

Simulation results of a DFIG controlled by the basic controller in combination with a first auxiliary controller have shown that following disturbances on the power network, the oscillatory variations in power output from the DFIG are dependent on variations in the “pseudo rotor angle” signal \( U_{aux1} \). Therefore, the power variations are similar to those produced by a synchronous generator subjected to the same network disturbance. However, a side effect of this is that for a network comprising at least one DFIG controlled in this way and at least one synchronous generator, oscillations from the DFIG are of a longer duration than for a DFIG controlled by the basic controller alone.

The provision of a synchronous generator like dynamic response helps to minimise the change produced in the network operating conditions as networks change from purely synchronous generators to a mix of generator types. This is of increasing importance as the proportion of electricity generated from wind farms increases. However, the first auxiliary controller in combination with the basic controller does not on its own offer any improvement to the dynamic response of the network as a whole.

Figure 9 illustrates the arrangement of the second auxiliary controller 62. This allows a controller for a DFIG to contribute to the damping of the power network.

For a synchronous generator, disturbances on the network produce oscillations in the rotor speed and the rotor angle. The variations in the currents of the generator windings produced by the rotor angle oscillations determine the damping contribution of the generator to the network. The currents generated due to the rotor oscillations produce a damping component of generator torque (and therefore power).
For a DFIG, under oscillatory network conditions, the variations produced in the rotor and stator currents also give rise to energy dissipation in the resistance of the windings. While this does provide some damping to the network the contribution is quite small.

However, by measuring a network variable that is appropriately excited by network oscillations (for instance rotor speed $\omega_r$, power supply $P_e$, stator frequency $\omega_s$ or slip $s$) the angular position of the rotor flux vector $\Psi_{r_ang}$ can be manipulated in such a way that damping torques are induced in of the synchronous generators on the network. Therefore, a significant contribution to system damping can be provided. The variation in the rotor flux vector angular position reference value $\Psi_{r_angref}$ is given by $U_{aux2}$.

The second auxiliary control signal $U_{aux2}$ can be calculated by passing the appropriate network variable through a washout filter 80, to remove any steady state contribution and prevent the second auxiliary controller from operating during steady state conditions. The signal is then passed through a compensator 81 to provide the necessary phase shift and an amplifier 82 to provide the necessary gain. The compensator and the amplifier provide variations in the demanded angular position of the rotor flux vector of sufficient magnitude and appropriate phase with respect to the network oscillations that increased damping torques are induced in the synchronous generators on the network. Finally, the signal is passed through an output value limiter 83 to provide the second auxiliary control signal $U_{aux2}$.

The second auxiliary controller 62, when based on rotor speed $\omega_r$, slip speed $s$ or stator electrical power supply $P_e$, can be used to provide improved system damping either independently or in combination with either the first or the third auxiliary controllers. Simulation results indicate that a network incorporating at least one DFIG controlled by a controller including a second auxiliary controller has an appreciable improvement in the damping of the synchronous generators on the network, compared with a network comprising synchronous generators alone. Additionally, the performance of the second auxiliary controller, when based on rotor speed $\omega_r$, slip speed $s$ or stator electrical power supply $P_e$, continues to provide significant improvements in network damping when operated in combination with the first auxiliary controller. Therefore, this nullifies the relatively poor dynamic
performance of the DFIG controller when operated with only the first auxiliary controller. However, it is preferable not to operate the second auxiliary controller with the first auxiliary controller when the second auxiliary controller uses an external system variable such as network frequency as the control input variable.

Referring now to Figure 10, this illustrates the arrangement of the third auxiliary controller 63. Network frequency is fixed by the synchronous generators on the network. When a loss of power generation occurs on the network due to one or more generators failing the network frequency falls rapidly. The generators allocated for frequency regulation that remain connected then need to increase power output as rapidly as possible, to avoid the network frequency falling below the level that demands load disconnection.

With conventional synchronous generators the increase in power output of the regulating generators is achieved via turbine governor action and therefore the rate of rise of the power supplied is limited. With a DFIG, although the input power of the wind turbine cannot be increased on demand, the asynchronous operation of a DFIG enables the stored mechanical energy of the rotor shaft system to be tapped to provide a rapid increase in generated power over the critical first few seconds following loss of network generation. The rotor shaft system comprises the turbine and the generator rotors together with the connecting gear box. The kinetic energy these hold can be rapidly converted to electrical energy to provide a temporary boost in the power supply $P_o$, at the expense of slowing the rotational speed of the rotor shaft system.

The third auxiliary controller 63 comprises an inner control loop 90, which serves to drive down the rotor speed over the initial period following loss of power generation, so that stored energy is released, and output power temporarily increased. The stator frequency $\omega_s$ (which is equal to and set by the network frequency) is processed to provide a rotor speed reference point $\omega_{\text{ref}}$.

The stator frequency signal $\omega_s$ is passed through a washout filter 91 to eliminate any steady state contribution and then through a first compensator 92, an output value limiter 93 and a second compensator 94 to provide the required transient profile for the rotor speed reference set point $\omega_{\text{ref}}$. A measure of the rotational speed of the rotor shaft system is passed through a washout filter 95 to remove any steady state condition. The measure may be based on the rotor speed $\omega_r$ or the slip signal $s$. 
The signal is then compared with the rotor speed reference point $\omega_{\text{ref}}$ at summing junction 96 to provide an auxiliary error signal. The auxiliary error signal is passed through a compensator 97 that offers the facility for adjusting the loop stability margins, to provide the third auxiliary control signal $U_{\text{aux3}}$. Compensator 97 is arranged to provide lead lag compensation.

The effect of the third auxiliary control signal $U_{\text{aux3}}$ is to increase the rotor flux vector angular position reference value $\Psi_{\text{rangref}}$. This produces an increase in generator torque and a consequent reduction in rotor speed $\omega_r$. The rotor speed is driven down to follow the transient swing in the derived rotor speed reference set point $\omega_{\text{ref}}$. The rotor speed $\omega_r$ returns to the original value when the network has returned to a steady state condition.

The third auxiliary controller 63 may be operated on its own or with the second auxiliary controller 62. However, the effect of driving down the rotor speed causes the first auxiliary controller 61 to have a negative effect. Therefore, if the third auxiliary controller 63 is used in combination with the first auxiliary controller 61, then when a loss of network generation is detected the first auxiliary controller is preferably temporarily inhibited or disconnected.

Simulation results have indicated that where loss of generation due to the tripping of synchronous generator occurs on a network including a DFIG controlled by a controller having a third auxiliary controller, the DFIG provides a significant increase in its power supply $P_e$ over the first few seconds. Consequently, the fall off of network frequency is less severe that for a network comprising only synchronous generators.

In the embodiment illustrated in Figure 7, the auxiliary control signals $U_{\text{aux1}}$, $U_{\text{aux2}}$, $U_{\text{aux3}}$ are shown being added to the rotor flux vector angular position reference value $\Psi_{\text{rangref}}$ in order to modify the signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector. As an alternative, the auxiliary control signals may be added to the power supply reference $P_{\text{eref}}$ either individually or in combination at summing junction 26 as illustrated in Figure 11. Whether added individually or in combination the auxiliary control signals indirectly modify the signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector. Figure 11 illustrates another embodiment of the present invention.
Components in Figure 7 that are similar to components in Figure 7 are referred to using the same reference number.

The auxiliary controllers 61, 62, 63 effectively manipulate the power supply reference value $P_{\text{ref}}$, and therefore indirectly the value of the signal indicative of the desired angular position of the rotor flux vector $\mathbf{\psi}_{\text{ref}}$. The arrangement of the auxiliary controllers remains the same as before, with gain and phase shift requirements altered to suit the new arrangement of the controller 101.

The auxiliary control loops can be used to modify the power supply reference value $P_{\text{ref}}$ in general for any DFIG control scheme employing a power (or torque) feedback loop. Such auxiliary control loops can provide similar benefits in terms of a synchronising power characteristic, network damping and network frequency regulation to a generic DFIG controller, as provided to the controller illustrated in Figure 11. This additional embodiment of the present invention is illustrated in Figure 12.

Controller 110 has a power supply feedback loop and may optionally have one or more feedback loops monitoring other parameters of the DFIG’s operation, as shown by the variable A feedback loop. The variable A feedback loop comprises an input measured value of parameter A derived from sensors connected to the DFIG and an input reference value for parameter A. An error signal $A_{\text{err}}$ is calculated. This error signal $A_{\text{err}}$ is used as an input to the controller. Components that are similar in Figures 11 and 12 are referred to by the same reference numbers. Sub-controller 111 converts the measured error signals to the desired rotor voltage vector $\mathbf{V}_{\text{r_dem}}$.

In accordance with a further embodiment of the present invention the auxiliary control signals $U_{\text{aux1}}$, $U_{\text{aux2}}$, $U_{\text{aux3}}$ can be used to modify the signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector by modifying the desired angular position of the rotor voltage vector $\mathbf{V}_{\text{r_dem}}$. One example of this implementation is illustrated in Figure 13, where only the second auxiliary control signal $U_{\text{aux2}}$ is shown being added to the desired angular position of the rotor voltage vector $\mathbf{V}_{\text{r_dem}}$ at summing junction 121. It will be appreciated that all three auxiliary control signals can be added to the desired angular position of the rotor voltage vector $\mathbf{V}_{\text{r_dem}}$ at summing junction 121. Components that are similar in Figures 7 and 13 are referred to using the same reference numbers.
When used to modify the desired angular position of the rotor voltage vector $V_{\text{rangdem}}$ the auxiliary controllers 61, 62, 63 effectively manipulate the value of the signal indicative of the desired angular position of the rotor flux vector $\Psi_{\text{rangref}}$. The auxiliary controllers remain the same as in Figures 8, 9 and 10, with gain and phase shift requirements altered to suit the new arrangement of the controller 120.

It is normally only desirable to shift the point of addition of the second auxiliary control signal $U_{\text{aux2}}$, as the other two auxiliary control signals have a slower speed of response to changes in their input parameters. The second auxiliary controller 62, which corresponds to a power system stabiliser, is preferably applied to the desired angular position of the rotor voltage vector $V_{\text{rangdem}}$. In order to provide rapid and effective damping, the second auxiliary controller is preferably able to modify the signal indicative of the desired angular position of the rotor flux vector $\Psi_{\text{rangref}}$ as directly as possible. By applying the second auxiliary control signal $U_{\text{aux2}}$ to the output of sub controller 29, the provision of damping is more readily facilitated.

When the second auxiliary controller 62 uses an external system variable such as network frequency as the control input variable the first auxiliary controller 61 is preferably disabled in order to avoid detrimental interaction.

The auxiliary control loops can be used to modify the desired angular position of the rotor voltage vector $V_{\text{rangdem}}$ for any DFIG control scheme employing a power (or torque) feedback loop. As such the auxiliary control loops may provide similar benefits as provided to the controller of Figure 13 in terms of a synchronising power characteristic, network damping and network frequency regulation to a generic DFIG controller. This additional embodiment of the present invention is illustrated in Figure 14, which shows the second auxiliary control signal $U_{\text{aux2}}$ being applied to the desired angular position of the rotor voltage vector $V_{\text{rangdem}}$ at a summing junction 131. The other two auxiliary control signals are arranged to alter to power supply reference value $P_{\text{ref}}$.

Controller 130 has a power supply feedback loop. Controller 130 may optionally have one or more feedback loops monitoring other parameters of the DFIG’s operation, as shown by the variable A feedback loop, as described above in relation to Figure 12. Similar components in Figures 12 and 14 are referred to by the
same reference numbers. Sub-controller 132 converts the measured error signals to the desired rotor voltage vector \( \mathbf{V}_{\text{r,dem}} \).

As a further option, the auxiliary control signals can be applied to alter desired angular position of the rotor voltage vector \( \mathbf{V}_{\text{rang,dem}} \) for any DFIG controller, which is arranged to provide a control signal comprising the rotor voltage vector \( \mathbf{V}_{\text{r,dem}} \). In such an implementation the auxiliary controllers provide similar benefits in terms of a synchronising power characteristic, network damping and network frequency regulation to any generic DFIG controller. An example of such an additional embodiment of the present invention is illustrated in Figure 15.

Controller 140 has two feedback loops monitoring parameters of the DFIG’s operation, depicted as the variable A feedback loop and the variable B feedback loop. Each feedback loop shown has as an input a reference value \( \mathbf{A}_{\text{ref}} \) and \( \mathbf{B}_{\text{ref}} \) respectively. These reference values are supplied to the controller along with measured values of the variables A and B. The measured values and the reference values are used in the respective feedback loops to generate error signals \( \mathbf{A}_{\text{err}} \) and \( \mathbf{B}_{\text{err}} \). Variables A and B may be any measured or calculated parameter relating to the DFIG. Similar components in Figures 12 and 15 are referred to by the same reference numbers. Sub-controller 141 converts the measured error signals to the desired rotor voltage vector \( \mathbf{V}_{\text{r,dem}} \). Figure 15 shows all three auxiliary control signals being applied to the desired angular position of the rotor voltage vector \( \mathbf{V}_{\text{rang,dem}} \) at summing junction 142. However, in most implementations only the second auxiliary control input \( U_{\text{aux2}} \) is used in order to provide more effective damping to the network. Applying any of the auxiliary control signals to the desired rotor voltage vector \( \mathbf{V}_{\text{r,dem}} \) can improve overall dynamic performance. However, it is only for the secondary auxiliary controller that there is any benefit to the performance of the controller for improving the network damping.

It will be readily appreciated from the teaching herein that the auxiliary control inputs \( U_{\text{aux1}}, U_{\text{aux2}}, U_{\text{aux3}} \) can be used to modify the performance of the DFIG by adding them into the controller at different points and in different combinations. In particular, where applicable the auxiliary control inputs \( U_{\text{aux1}}, U_{\text{aux2}}, U_{\text{aux3}} \) may be added to any one or more of the rotor flux vector angular position reference value \( \Psi_{\text{rang,ref}} \), the power supply reference value \( P_{\text{er,ref}} \) and the desired angular position of the
rotor voltage vector $\mathbf{V}_{\text{rangdem}}$. In each case, one, two or three auxiliary control inputs may be added to the controller at each point. The three auxiliary controllers 61, 62, 63 need not all be present for all DFIG controllers. Indeed, for many applications only the second auxiliary controller 62 is likely to be used to modify the desired angular position of the rotor voltage vector $\mathbf{V}_{\text{rangdem}}$ to provide a power system stabiliser capability for any generic DFIG controller.

It will be readily apparent to the appropriately skilled person that embodiments of the present invention can be implemented using measurement of rotor torque as opposed to the output stator electrical power supply. The two quantities are directly linked.

Air gap power is given as:

$$P_{\text{airgap}} = T_e \omega_s$$

$T_e$ is the generator torque and $\omega_s$ is the stator frequency (the rotational speed of the stator flux vector), at nominal frequency, $\omega_s = 1$ in per unit terms, so that air gap power in per unit terms and torque in per unit terms are directly equivalent. Stator power differs from the air gap power only by the resistance losses of the stator. As stator power is more readily determined from the available voltage and current measurements this is the preferred choice. Stator power is given by:

$$P_e = \mathbf{V}_s \mathbf{I}_s^*$$

where $\mathbf{V}_s$ is the stator terminal voltage vector and $\mathbf{I}_s$ is the stator current.

Generator torque is given by:

$$T_e = \frac{1}{\omega_s} \left( P_e - R_s |\mathbf{I}_s|^2 \right)$$

where $R_s$ is the stator resistance.

The controller described herein can be viewed in terms of manipulating the rotor flux vector $\mathbf{\Psi}_r$ or the internally generated voltage $E_{\text{sig}}$ as these terms are directly related.

The controller may be implemented in hardware. Alternatively the controller may be implemented in software.

Although primarily described above in terms of a controller for a DFIG within a wind farm, embodiments of the present invention may be equally applied to the
control of any DFIG connected to any power source. The auxiliary controllers may be implemented within any DFIG controller in any combination.

Further modifications and applications of the present invention will be readily apparent to the appropriately skilled person based on the teaching herein.
CLAIMS

1. A controller for a doubly-fed induction generator, the doubly-fed induction generator comprising:

   a stator comprising stator terminals arranged to provide a three phase stator terminal voltage supply, and a three phase winding arranged to provide a stator flux described by a vector rotating at a stator frequency, and arranged to provide a stator electrical power supply at the stator frequency; and

   a rotor comprising a three phase winding arranged to provide a rotor flux described by a vector rotating at substantially the stator frequency at an angular position relative to the stator flux vector;

   wherein the controller is arranged to determine a control signal to cause a change substantially only in the magnitude of the rotor flux vector in response to a stator terminal voltage error signal, and to determine a control signal to cause a change substantially only in the angular position of the rotor flux vector relative to the stator flux vector, in response to a stator electrical power supply error signal.

2. A controller according to claim 1, wherein the stator terminal voltage error signal is indicative of the difference between the magnitude of the stator terminal voltage and the magnitude of a predetermined stator terminal voltage reference signal.

3. A controller according to claim 1 or claim 2, wherein the stator electrical power supply error signal is indicative of the difference between the stator electrical power supply and a predetermined stator electrical power supply reference signal.

4. A controller according to any one of the preceding claims, wherein the stator electrical power supply is indicative of a torque exerted by the rotor.

5. A controller according to any one of the preceding claims, wherein the control signals are indicative of a desired rotor voltage described by a vector, for supply to the rotor three phase winding.
6. A controller according to any one of the preceding claims, wherein the controller is arranged to output said control signals in polar coordinate form relative to a reference frame rotating at the stator frequency.

7. A controller according to any one of the preceding claims, wherein the controller is arranged to output said control signals in rectangular coordinate form relative to a reference frame rotating at the stator frequency.

8. A controller according to any one of the preceding claims, arranged to determine said control signals by comparing a rotor flux vector magnitude reference value and a value indicative of the actual magnitude of the rotor flux vector and comparing a rotor flux vector angular position reference value and a value indicative of the actual angular position of the rotor flux vector relative to the stator flux vector.

9. A controller according to any one of the preceding claims, wherein the controller comprises a first compensator arranged to receive the stator terminal voltage error signal and determine a rotor flux vector magnitude reference value.

10. A controller according to claim 9, wherein the first compensator comprises a proportional plus integral controller and a phase compensation element.

11. A controller according to any one of the preceding claims, wherein the controller comprises a second compensator arranged to receive the stator electrical power supply error signal and determine a rotor flux vector angular position reference value relative to the stator flux vector angular position.

12. A controller according to claim 11, wherein the second compensator comprises a proportional plus integral controller and a phase compensation element.

13. A controller according to any one of the preceding claims, wherein the controller further comprises at least one auxiliary controller, each auxiliary controller being arranged to determine an auxiliary control signal in response to at least one of a
rotor speed signal, a stator electrical power supply signal, a slip signal and a stator frequency signal, the controller being arranged to utilise the auxiliary control signal to modify the value of a signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector.

14. A controller according to claim 13, wherein a first auxiliary controller is arranged to determine a first auxiliary control signal from a first auxiliary input signal comprising at least one of the rotor speed signal and the slip signal, the first auxiliary controller comprising a washout filter, an integrator, a compensator and an output value limiter.

15. A controller according to claim 13 or 14, wherein a second auxiliary controller is arranged to determine a second auxiliary control signal from a second auxiliary input signal comprising at least one of the rotor speed signal, the stator electrical power supply signal, the slip signal and the signal indicative of the stator frequency, the second auxiliary controller comprising a washout filter, a compensator, an amplifier and an output value limiter.

16. A controller according to any one of claims 13 to 15, wherein a third auxiliary controller is arranged to determine a third auxiliary control signal from the stator frequency signal and at least one of the rotor speed signal and the slip signal, the third auxiliary controller being arranged to: determine a first resultant signal by washout filtering, first compensating, output value limiting and second compensating the stator frequency signal; determine a second resultant signal by washout filtering at least one of the rotor speed signal and the slip signal; determine an auxiliary error signal from the difference between the resultant signals; and determine the third auxiliary control signal by third compensating the auxiliary error signal.

17. A controller according to claim 16, when dependent upon claim 14, wherein the controller is arranged to selectively inhibit the operation of the first auxiliary controller.
18. A controller according to any one of claims 13 to 17 when dependent on claim 8, wherein the signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector comprises the rotor flux vector angular position reference value, and the controller is arranged to utilise at least one of the auxiliary control signals to modify the rotor flux vector angular position reference value relative to the stator flux vector angular position.

19. A controller according to any one of claims 13 to 18 when dependent on claim 3, wherein the signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector comprises the predetermined stator electrical power supply reference signal, and the controller is arranged to utilise at least one of the auxiliary control signals to modify the predetermined stator electrical power supply reference signal.

20. A controller according to any one of claims 13 to 19 when dependent on claim 5, wherein the signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector comprises an angular position of the desired rotor voltage vector, and the controller is arranged to utilise at least one of the auxiliary control signals to modify the angular position of the desired rotor voltage vector.

21. A doubly-fed induction generator comprising a controller according to any one of claims 1 to 20.

22. A method of controlling a doubly-fed induction generator, the doubly-fed induction generator comprising: a stator comprising stator terminals arranged to provide a three phase stator terminal voltage supply, and a three phase winding arranged to provide a stator flux described by a vector rotating at a stator frequency and arranged to provide a stator electrical power supply at the stator frequency; and a rotor comprising a three phase winding arranged to provide a rotor flux described by a vector rotating at substantially the stator frequency at an angular position relative to the stator flux vector; the method comprising:
determining a control signal to cause a change substantially only in the magnitude of the rotor flux vector in response to a stator terminal voltage error signal; and

determining a control signal to cause a change substantially only in the angular position of the rotor flux vector relative to the stator flux vector, in response to a stator electrical power supply error signal.

23. A controller for a doubly-fed induction generator, the doubly-fed induction generator comprising:

a stator comprising a three phase winding arranged to provide a stator flux described by a vector rotating at a stator frequency and arranged to provide a stator electrical power supply at the stator frequency; and

a rotor comprising a three phase winding arranged to provide a rotor flux described by a vector rotating at substantially the stator frequency at an angular position relative to the stator flux vector;

wherein the controller comprises at least one auxiliary controller, each auxiliary controller being arranged to determine an auxiliary control signal in response to at least one of a rotor speed signal, a slip signal, a stator frequency signal and a stator electrical power supply signal, the controller being arranged to utilise the auxiliary control signal to modify the value of a signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector.

24. A controller according to claim 23, wherein a first auxiliary controller is arranged to determine a first auxiliary control signal from a first auxiliary input signal comprising at least one of the rotor speed signal and the slip signal, the first auxiliary controller comprising a washout filter, an integrator, a compensator and an output value limiter.

25. A controller according to claim 23 or claim 24, wherein a second auxiliary controller is arranged to determine a second auxiliary control signal from a second auxiliary input signal comprising at least one of the rotor speed signal, the stator electrical power supply signal, the slip signal and the stator frequency signal, the
second auxiliary controller comprising a washout filter, a compensator, an amplifier and an output value limiter.

26. A controller according to any one of claims 23 to 25, wherein a third auxiliary controller is arranged to determine a third auxiliary control signal from the stator frequency signal and at least one of the rotor speed signal and the slip signal, the third auxiliary controller being arranged to: determine a first resultant signal by washout filtering, first compensating, output value limiting and second compensating the stator frequency; determine a second resultant signal by washout filtering at least one of the rotor speed signal and the slip signal; determine an auxiliary error signal from the difference between the resultant signals; and determine the third auxiliary control signal by third compensating the auxiliary error signal.

27. A controller according to claim 26, when dependent upon claim 24, wherein the controller is arranged to selectively inhibit the operation of the first auxiliary controller.

28. A controller according to any one of claims 23 to 27, wherein the controller is arranged to determine a control signal to cause a change substantially only in the stator electrical power supply, in response to a stator electrical power supply error signal indicative of the difference between the stator electrical power supply and a predetermined stator electrical power supply reference signal,

the signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector comprises the predetermined stator electrical power supply reference signal, and

the controller being arranged to utilise at least one of the auxiliary control signals to modify the predetermined stator electrical power supply reference signal.

29. A controller according to any one of claims 23 to 28, wherein the signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector comprises a signal indicative of a desired rotor voltage described by a vector, for supply to the rotor three phase winding, and the controller is arranged to
utilise at least one of the auxiliary control signals to modify the angular position of the desired rotor voltage vector.

30. A doubly-fed induction generator comprising a controller according to any one of claims 23 to 29.

31. A method of controlling a doubly-fed induction generator, the doubly-fed induction generator comprising: a stator comprising a three phase winding arranged to provide a stator flux described by a vector rotating at a stator frequency and arranged to provide a stator electrical power supply at the stator frequency; and a rotor comprising a three phase winding arranged to provide a rotor flux described by a vector rotating at substantially the stator frequency at an angular position relative to the stator flux vector; the method comprising:

   determining an auxiliary control signal in response to at least one of a rotor speed signal, a slip signal, a stator frequency signal and the stator electrical power supply signal; and

   utilising the auxiliary control signal to modify the value of a signal indicative of the desired angular position of the rotor flux vector relative to the stator flux vector.

32. A data carrier carrying computer program code means to cause a computer to carry out the method according to claim 22 or 31.

33. A computer apparatus comprising:

   a program memory containing processor readable instructions; and

   a processor for reading and executing the instructions contained in the program memory;

   wherein said processor readable instructions comprise instructions controlling the processor to carry out the method according to claim 22 or 31.

34. A controller for a doubly-fed induction generator, substantially as hereinbefore described, with reference to the accompanying drawings.
35. A doubly-fed induction generator, substantially as hereinbefore described, with reference to the accompanying drawings.

36. A method of controlling a doubly-fed induction generator, substantially as hereinbefore described, with reference to the accompanying drawings.

37. A data carrier carrying computer program code means, substantially as hereinbefore described, with reference to the accompanying drawings.

38. A computer apparatus, substantially as hereinbefore described, with reference to the accompanying drawings.
FIG 12
## INTERNATIONAL SEARCH REPORT

### A. CLASSIFICATION OF SUBJECT MATTER
- H02P21/10
- H02P21/05
- F03D9/00
- F03D7/02
- H02P9/00
- H02P9/48

According to International Patent Classification (IPC) or to both national classification and IPC.

### B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
- H02P
- F03D
- H02K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched:

Electronic data base consulted during the international search (name of database and, where practical, search terms used)
- EPO-Internal

### C. DOCUMENTS CONSIDERED TO BE RELEVANT

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### X Further documents are listed in the continuation of box C.

### X Patent family members are listed in annex.

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Date of the actual completion of the international search: 20 December 2005

Date of mailing of the international search report: 04/01/2006

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<td>EP 0 817 367 A (HONDA GIKEN KOGYO KABUSHIKI KAISHA) 7 January 1998 (1998-01-07) abstract column 6, line 8 - line 14 column 9, line 37 - line 38 claims 1,2 figure 1</td>
<td>1,22,23, 31-38</td>
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