Method of Conversion of Double Fed Machine Into Synchronous Operation Mode and its Simulation

L.H. Hasanova

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Azerbaijan Scientific-Research and Disigned-Prospecting Institute of Energetics, Baku, Azerbaijan AZ1012, Aven. H.Zardabi-94
e-mail: mustafayevri@mail.ru

Abstract

Double fed induction machines, made on the base of wound rotor machines, thanks to the rapid progress in the converter equipment (due to widespread use of fully controlled thyristors and power transistors) nowadays are widely used as generators (wind power and small hydropower) as well as the motor-where relatively small speed adjustment range (30-40%) is required, by restrictions of the frequency inverter on the installed capacity. There are cases when the technology of their application as a generator and motor mode imposes their long-term operation in sub-synchronous rotational speed, i.e, without speed control. In this case, it is proposed to use only the rectifier side of the frequency inverter feeding the rotor winding of a double fed induction machines, switch into a synchronous mode of operation. This will greatly increase the delivery of reactive power into the grid and use the generator more efficiently. Presented a developed mathematical model of double fed induction machines, which allows to study of all operation modes of double fed induction machines in single set-up–by immediate designation (sub- and super-synchronous speed control); in synchronous generator mode with a significant reactive power output into the grid, as well as in squirrel cage induction generator mode.

Keywords: double fed machine, synchronous operation mode, simulation, method of conversion.

Introduction

In recent years the double fed asynchronous machines (DFAM) are widely used as the generators of wind power plants [1, 2, 3]. They are also recommended for using as the generators in hydraulic units of small hydroelectric power plants (HPP) [4,5].

Range of their application as the motors is also extensive: they are in demand where the rotational frequency of drive mechanism needs to be controlled in relatively small ranges (30-40% of the rated one) under the limited power of frequency converter, supplying the rotor's winding of DFAM.

However, the cases often occur depending on the requirements of either electric power generation technology with DFAM operating in generator mode or the technology of drive mechanism operating with DFAM as a motor, when within a long time it is not required to control the rotational frequency of either turbine (driving motor) or operating mechanism. For example, when the hydraulic units of small HPSs are equipped with propeller turbines, it needs to control the rotational frequency of generator with essential increase (or decrease) of the water flow.

Exactly with this change of water flow (discharge) the control of rotational frequency of the hydraulic unit's shaft proportionally with the change of this water discharge by force of AMDP allows raising the efficiency of hydraulic turbine, and in addition to that the output power of hydraulic unit supplying the electric power network. When water discharge is constant (and this period may go on for a long time), it is reasonable the rotational frequency to remain constant.

With frequency converter in rotor's circuit of AMDP it can be implemented by the following ways: either to remove the frequency converter from the operating mode, and then to short-circuit the rotor windings of DFAM, thereby this machine will be converted into squirrel-cage asynchronous generator, or to leave the frequency converter in operation with adjusting it so, that the rotational frequency of generator will be nearly equal to synchronous one. In the first case it is clear that the power factor of generator will be the low one, i.e. generator will consume the significant reactive power from the network. In the second case, the power factor will be in the limits of cos$\varphi\approx$1, (i.e. generator doesn't consume, but also doesn't output the reactive power)..

1. Statement of a problem

To increase the output of reactive power into network a rotor winding of DFAM is offered to connect to a power source of direct current, i.e. to convert DFAM into operating mode of synchronous machine. This will allow providing with reactive power the load center of power system, to which the DFAM is connected, in addition the machine can be loaded up to full rated power.

The electrical schematic diagram of conversing of DFAM with frequency converter in rotor circuit into synchronous operating mode can be presented in the view, shown in Fig.1:

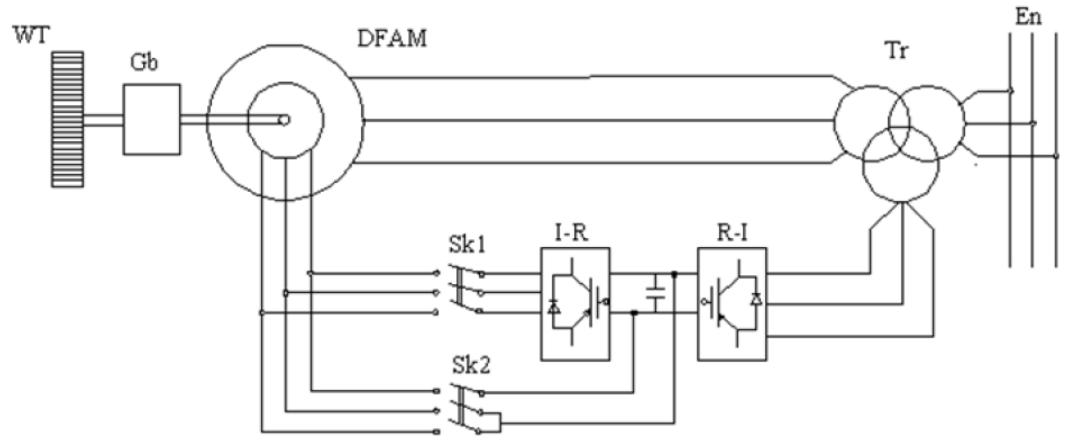

Figure.1 Electrical diagram of conversing of DFAM with frequency converter in rotor circuit into synchronous operating mode

Here WT–is a driving turbine (e.g. water one), it is aggregated by force of the gearbox Gb with the shaft of generator, carried out on the basis of double fed machine DFAM, Tr–a three-winding transformer, supplying the stator and rotor windings of DFAM, En–electric power network (system), I-R and R-I–inverter–rectifier, carried out on the basis of fully controlled IGBT–transistors, or GTO–thyristors, Sk1, Sk2–switching keys (switches).

The circuit diagram of connection of rotor windings of asynchronous machine with phase-wound rotor, shown in Fig.1, is known from [6], the originality of this diagram lies in the fact that, the rotor windings are suppled in a synchronous mode from a link of direct current of frequency converter, assigned for controlling of rotational frequency of aggregate in operating mode controlled from the rotor side of DFAM.

2. Mathematical model for study

Let's demonstrate the performance of above proposal on previously developed by us the mathematical model of DFAM (system is supplemented with the expressions for active and reactive powers of stator and rotor) [1]. Equations of DFAM, frequency controlled from the rotor side, are presented in the view [in relative units]:

$$\left.\begin{aligned}
&p\Psi_{ds} = -U_s \cdot sin\theta + \psi_{qs}(1-s) - r_s \cdot i_{ds}\\
&p\Psi_{qs} = U_s \cdot cos\theta - \psi_{ds}(1-s) - r_s \cdot i_{qs}\\
&p\psi_{dr} = -k_{ur} \cdot sin(k_{fr} \cdot \tau) - r_r \cdot i_{dr}\\
&p\psi_{qr} = \pm k_{ur} \cdot cos(k_{fr} \cdot \tau) - r_r \cdot i_{qr}\\
&ps = \frac{1}{T_j} m \frac{1}{T_j}_{em_{WT}}\\
&p\theta = s\\
&m_{em} = \psi_{ds} \cdot i_{qs} - \psi_{qs} \cdot i_{ds}\\
&p_s = U_{ds} \cdot i_{ds} + U_{qs} \cdot i_{qs}\\
&q_s = U_{qs} \cdot i_{ds} - U_{ds} \cdot i_{qs}\\
&p_r = U_{dr} \cdot i_{dr} + U_{qr} \cdot i_{qr}\\
&q_r = U_{qr} \cdot i_{dr} - U_{dr} \cdot i_{qr}\\
&i_{ds} = k_s \cdot \psi_{ds} - k_m \cdot \psi_{dr}\\
&i_{qs} = k_s \cdot \psi_{qs} - k_m \cdot \psi_{qr}\\
&i_{dr} = k_r \cdot \psi_{dr} - k_m \cdot \psi_{ds}\\
&i_{qr} = k_r \cdot \psi_{qr} - k_m \cdot \psi_{qs}\\
&p_{tot} = p_s + p_r\\
&q_{tot} = q_s + q_r
\end{aligned}\right\} \tag{1}$$

In the system of equations (1) the following designations: Ψ_{ds}, Ψ_{qs}, Ψ_{dr}, Ψ_{qr} – are accordingly the flux linkages of stator and rotor circuits on direct and quadrature axes; i_{ds}, i_{qs}, i_{dr}, i_{qr} – currents of stator and rotor windings on d and q axes; U_s – amplitude of voltage applied to the stator winding of machine; k_{ur}, k_{fr} – amplitude and frequency of controlled by frequency converter voltage, supplied to the rotor windings of machine; s – slip of the machine equal to s=1– ω_r; ω_r – angular frequency of revolution; θ – angle between the axis of rotor and synchronously rotating axis (with speed $\omega_s = 1$); m_{WT}, m_{em} – driving torque of the driven motor (e.g. water turbine) and electromagnetic torque of DFAM; $U_{ds}= -U_s \cdot \sin(\theta)$ and $U_{qs}=U_s \cdot \cos(\theta)$ – components of stator voltage on d and q axes; $U_{dr}= -k_{ur} \cdot \sin(k_{fr} \cdot \tau)$, $U_{qr}=k_{ur} \cdot \cos(k_{fr} \cdot \tau)$ – components of rotor voltage on d and q axes; p_s, p_r – values of active powers of stator and rotor circuits; q_s, q_r – values of reactive powers of stator and rotor; p_{tot}, q_{tot} – total active and reactive powers of DFAM; T_j – inertia constant of the rotating parts of driving motor and DFAM; τ=314·t – synchronous time [in rad.].

Furthermore, the factors k_s, k_r and k_m are determined from the following correlations:

$$k_s = \frac{x_r}{x_r \cdot x_s - x_m^2};\ k_r = \frac{x_s}{x_r \cdot x_s - x_m^2};\ k_m = \frac{x_m}{x_r \cdot x_s - x_m^2} \tag{2}$$

DFAM parameters: r_s, r_r – resistances of stator and rotor windings; x_s, x_r – full inductive reactances of stator and rotor circuits; x_m – mutual induction reactance between stator and rotor circuits (they are the analogous of corresponding inductivities).

It should be noted that the system of equations (1) is written in d, q, axes, rotating with rotor speed ω_r of the machine. Exactly this circumstance allows realizing in one structure of mathematical model the operating modes of all conversions of double fed machine into squirrel-cage asynchronous machine, synchronous machine with the implementation of excitation system on one of axes (d axis).

The calculations have been performed for DFAM with the following parameters: P_n=110 kW; M_n=727.25 Nm; cosφ=0.9; η=0.95; U_{base}=311 V; I_{base}=285 A; Z_{base}=1.09 ohm; J=0.86 kgm^2. The winding data (in relative units) r_s=0.01; r_r=0.03; x_s=4.878; x_r=4.9; x_m=4.8; $x_{\sigma s}$=0.078; $x_{\sigma r}$=0.1 (resistances and reactances of leakage of stator and rotor windings).

Algorithm of solution (Mathcad program) with the numerical data is presented below:

$$\boldsymbol{D(\tau,Y)} = \begin{bmatrix} -1\cdot sin(Y_6)+Y_2-Y_5\cdot Y_2-0.01\cdot(5.69\cdot Y_1-5.56\cdot Y_3) \\ 1\cdot cos(Y_6)-Y_1+Y_5\cdot Y_1-0.01\cdot(5.69\cdot Y_2-5.56\cdot Y_4) \\ -k_{ur}\cdot sin(k_{fr}\cdot\tau)-0.03\cdot(5.66\cdot Y_3-5.56\cdot Y_1) \\ \pm k_{ur}\cdot cos(k_{fr}\cdot\tau)-0.03\cdot(5.66\cdot Y_4-5.56\cdot Y_2) \\ 0.005\cdot m[Y_1\cdot(5.69\cdot Y_2-5.56\cdot Y_4)-Y_2\cdot(5.69\cdot Y_1-5.56\cdot Y_3)]_{WT} \\ Y_5 \end{bmatrix} \tag{3}$$

where: Y_1=Ψ_{ds}; Y_2=Ψ_{qs}; Y_3=Ψ_{dr}; Y_4=Ψ_{qr}; Y_5=s; Y_6=θ. The initial values of all variables Y_0=0, besides Y_{05}=1 (slip s_0=1).

3. Study of Double Fed Induction Machine in Synchronous Operation Mode

As it was mentioned above, in a long-time operating mode two options are possible in a range near synchronous rotational frequency. In the first option the frequency converter can be removed from the operation (Fig.1) and rotor windings short-circuited, thus DFAM converts into squirrel-cage asynchronous generator. In this case, equations (3) and (4) of the system (1) will appear as:

$$\left.\begin{aligned} p\psi_{dr} &= -r_r\cdot i_{dr} \\ p\psi_{qr} &= -r_r\cdot i_{qr} \end{aligned}\right\} \tag{4}$$

Since U_{dr} and U_{qr}, k_{ur} and k_{fr} are equal to zero, the equations for p_r and q_r will also disappear from the system (1) (i.e. equations 9 and 10).

In the second option, which is the most reasonable one, DFAM could be converted into the synchronous generator, thereto in the system of equations (1) the same equations (3) and (4) should be written as:

$$\left.\begin{aligned} p\psi_{dr} &= U_{df}-r_{df}i_{dr} \\ p\psi_{qr} &= -r_{qr}\cdot i_{qr} \end{aligned}\right\} \tag{5}$$

That is, the system (1) as a whole is transformed into the Park-Gorev equations with the implementation of excitation U_{df} on direct axis d of the machine .

According to Fig.1, a constant voltage is supplied to start U_{df} of rotor winding of phase A, and to joined together the starts of phases B and C, and the ends of these windings are joined together (zero point), i.e. phases B and C are connected in parallel to each other and serially with the phase A. When aligning the direct axis d with axis of winding of A phase, it can be considered with a certain error, that windings' axes of B and C phases are on the quadrature axis q.

In consequence of such connection the resistances r_{df} = r_{dr} of the expression (4) should be increased by 1.5 times, i.e. r_{rf} =r_{dr}=1.5$\cdot r_r$, and the resistance r_{qr} will be equal to r_{rq}=2$\cdot r_r$. With a fractional error it can be considered that the leakage reactances of rotor circuits $x_{\sigma dr}$=1.5$\cdot x_{\sigma r}$ change in the same ratio; $x_{\sigma qr}$=2$\cdot x_{\sigma r}$. This naturally will entail the changes of rotor circuits' impedances x_{dr} and x_{qr}, and values k_s, k_r and k_m in the system of equations (1).

With taking into account the parameters of machine and circuit diagrams of rotor winding according to Fig.1 the connection of currents with flux linkages in this mode will appear in the following digital form:

$$\left.\begin{aligned} i_{ds} &= 4.5\cdot\psi_{ds}-4.36\cdot\psi_{dr} \\ i_{qs} &= 3.7\cdot\psi_{qs}-3.55\cdot\psi_{qr} \\ i_{dr} &= 4.43\cdot\psi_{dr}-4.36\cdot\psi_{ds} \\ i_{qr} &= 3.61\cdot\psi_{qr}-3.55\cdot\psi_{qs} \end{aligned}\right\} \tag{6}$$

Let's demonstrate the above calculations on the same structure of mathematical model of DFAM.

There are presented in the Fig.2 (*a, b, c, d, e, f, g, h*) accordingly the electromagnetic torque of the machine m_{em}, its rotational frequency ω_r, active and reactive powers of generator p_s and q_s and stator's currents i_{ds} and i_{qs} and rotor's ones i_{dr} and i_{qr}.

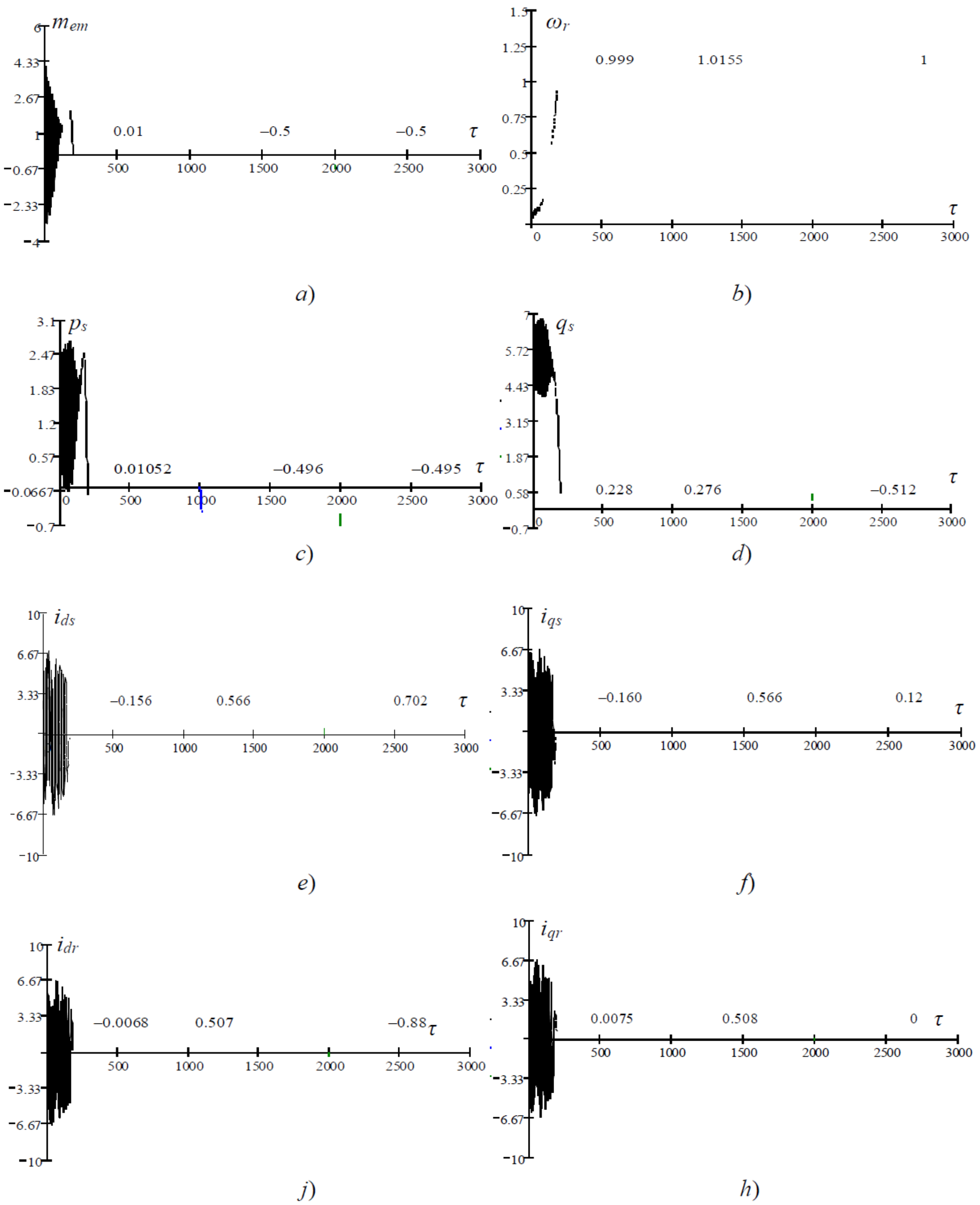

Figure.2 The fluktogrammas of change of double fed asynchronous machine's operating conditions when operating in synchronous mode.

Startup is carried out with taking into account the friction torque equal to m_{WT}=0.01 (i.e. practically without load) in the time period of from τ=0 to τ=1000 radian. Wherein the rotation frequency ω_r=0.999. From τ=1000 rad. to τ=2000 rad. the machine operates in asynchronous generator mode, with short-circuited rotor's windings when the driving torque of driven motor (turbine) is equal to m_{WT}= –0.5 (minus sign indicates generator mode). In this mode the electromagnetic torque m_{em}= –0.5 (Fig.2, a), rotational frequency ω_r=1.0155 (Fig.2, *b*), (ω_r>1which indicates the machine operation in generator mode). Active and reactive powers p_s and q_s equal to p_{tot} and q_{tot} in this mode reach the values p_s= –0.496 and q_s=0.276, and the reactive power is positive, i.e. generator consumes reactive power from the network (Fig.2, *c* and *d*). Stator currents i_{ds} and i_{qs} and rotor ones i_{dr} and i_{qr} in this mode are variables, the amplitude of stator currents does not exceed the values i_{ds}=i_{qs}=0.566, and the rotor ones i_{dr}=i_{qr}=0.508 (Fig.2, *e*, *f* and *i*, *j*).

On the fluktogrammas of the same figure in the time range of from τ =2000 rad. to τ =3000 rad. conversion into synchronous operating mode of the machine is carried out, i.e. equations (2) and (3) of the system (1) are formed according to the ratios (4) and (5). In this range the drive torque remains the same, i.e. m_{WT}= –0.5, according to it m_{em} = –0.5, rotational frequency is strictly equal to ω_r=1, which indicates the synchronous mode. For this machine the constant value of excitation voltage in the equations (4) is chosen to be equal to U_{df} = –0.04. In this process the active power value is equal to p_s= –0.495 (Fig.2, *c*) and reactive one is q_s= –0.512 (Fig.2, *d*). That is, the machine operates in synchronous mode with output to the network both an active and the reactive powers, and the value of reactive power is a little bit more than active one. Power factor has capacitive character and reaches the value of cosφ_{st}≈0.7.

In synchronous mode the stator and rotor currents (Fig.2, *e*, *f*) does not exceed the permissible limits. Excitation current i_{dr}=i_{df} sets at a level of i_{dr}=i_{df}= –0.889 (Fig.2, *g*), and current i_{dr} in this mode is naturally equal to i_{qr}=0 (Fig.2, *h*). It must be noted that operating mode of DFIM in near synchronous mode, values of the control parameters will be k_{ur}=k_{fr}=0.01 when m_{WT}=–0.5.

The electromagnetic torque sets at the value of m_{em}= –0.5, the rotational frequency is equal to ω_r=1.01, the active and reactive powers are accordingly equal to p_{tot}= –0.49, q_{tot} ≈ –0.03. Thus, DFIM operates in a design mode, and output of reactive power is almost equal to zero, i.e. generator operates with power factor equal to cosφ ≈1.

Summarizing the above-stated, the following algorithm of DFAM operation can be recommended under the long-term operating conditions (month, season) in a range of near synchronous speed for the average values of driving torque of driven motor: when a considerable reactive power output to network is required, AMDP should be transfered into operating mode of a purely synchronous generator with excitation from controlled rectifier (Fig.1), in this process the inverter (I-R) is removed from the circuit; when DFAM operating on partially compensated with reactive power the electric power network it is necessary to leave the circuit of frequency converter unchanged; to secure the near synchronous rotational frequency by the values of the control parameters (k_{ur}=k_{fr}), in this process the reactive power (cosφ≈1) isn't output to the network and isn't consumed from the network; and finally with significant compensation of reactive power to the electric network it is necessary to remove completely the frequency converter from the operating mode and to convert DFAM into squirrel-cage asynchronous generator mode, in this case the reactive power will be consumed from the network.

Conclusions

1. The presented notation of the equations of controlled double fed asynchronous machine allows relatively easy studying of the mathematical model of DFAM in one structure, conversion of the machine into the modes of synchronous generator and squirrel-cage asynchronous generator.
2. When DFAM operating on the uncompensated electric power networks and under the appropriate processing conditions it is advisable to convert its operation into a synchronous mode, connecting and powering the rotor windings according to the diagram on Fig.1 from the rectifier

part of frequency converter. This allows significant increasing of output of reactive power by generator into the network, while the value of the leading cosφ constitutes cosφ ≈0.7.

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