Turbines and Generators for Floating Solar Chimney Power Stations

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Abstract

Floating Solar Chimney Power Stations (FSCPSs) is a new promising solar technology. The Floating Solar Chimneys are lighter than air constructions, that can be as high as 3÷4.5 Km giving to their respective power stations efficiencies from 4.5÷7%. The axial shrouded air turbines of the FSCPSs are geared to appropriate electric generators. In the present paper the Doubly Fed induction generatos (DFIGs) , with small electronic control units (with power not more than 3.5 % of their generators rated power), are examined as the best and most economical solution.

Due to the FSCPSs characteristics, it can be proved that, at least 97% of the theoretically maximum production energy by the FSCPS can be supplied to the grid. The DFIGs can supply to the grid positive reactive power(on demand) ,and stabilize the grid when necessary.

FSCPSs with Doubly Fed induction generators can be used for autonomous hydrogen production combined with appropriate electrolysis units.

Key Words

Floating Solar Chimneys Doubly Fed Induction Generators

1. Introduction

The solar air turbine power stations were invented by prof. J. Schlaigh. In his book ref. [1] Schlaigh gives an extensive presentation for them. A solar chimney power station is mainly a set of three components:

- A large circular solar collector with a diameter Dc (the greenhouse)
- A tall chimney in its center with an internal diameter d and height H (the solar chimney)
- A set of shrouded air turbines geared to appropriate electric generators around the bottom of the solar chimney (the turbogenerators)

An indicative diagram for a STPS is shown in fig.1.

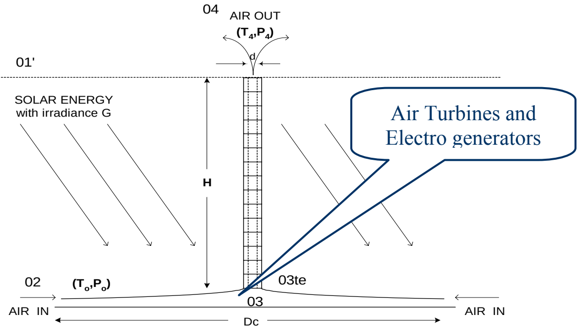

Fig.1

Due to greenhouse effect the air is warmed in the solar collector. The warm air is moving from the periphery of the solar collector to its center towards the entrance of the solar chimney, in order to ‘’escape’’ to upper layers of troposphere at the output of the solar chimney (see fig.1). This moving stream of warm air leaves part of its thermodynamic energy to the air turbines that are geared with appropriate electric generators. The axial air turbines can be placed with horizontal axis in a perimeter around the bottom of the solar chimney, or vertically inside the solar chimney. Prof. Schlaigh believes that concrete solar chimneys up to 1000 m height, can be constructed.

The author with his invention [2], proposed to make solar chimneys as lighter than air constructions, made by light enduring fabric, that are used in balloon and airship industry. The author believes that such constructions, that can float in the air and were named Floating Solar Chimneys (FSCs), can encounter effectively the operational sub pressure and the external winds. In paper [3] a presentation of the properties and operational characteristics, of STPSs with FSCs was given.

In paper [4 the performance of the FSCs under external winds was presented.

In paper [5] an extensive study for the power output and efficiency of STPSs with FSCs was given.

The Floating Solar Chimney Power Stations (FSCPSs) have the following advantages over the reinforced concrete solar chimney power stations or “Solar Towers” as they called :

- The concrete Solar Chimney is a huge and difficult construction and thus very expensive. The sole function of it is to updraft the warm air of the greenhouse to the upper layers of the atmosphere.
- The same function can be executed with the Floating Solar Chimney that is a simple lighter than air

construction, much cheaper than the respective concrete chimney.

- The concrete chimney has a construction height limit (about 1000m) related with the weight and strength of concrete and steel. This height defines the efficiency of its solar power station to less than 1%. The Floating Solar Chimney has no such limit. Thus can become 3 – 4,5 km high, up drafting the warm air with a proportional to this height force to the upper layers of the atmosphere, and thus giving to its solar power station efficiencies from 4,5% to 7%.
- For the same output power its solar collector area is 4,5 to 7 times smaller, thus the overall cost of its respective power station is less than 850 $/KW (see ref.[6]) while the equivalent concrete Solar Chimney power station has a cost of 3.500 $/KW, producing annually the same electric energy (approximately 3000 KWh per rated KW).

In the present paper a study of FSCPSs connected to the electric grid with induction generators is given. The squirrel cage induction generators are very simple in operation with minimum cost and maintenance. However they absorb reactive power by the grid. Using Doubly Fed Induction Generators (DFIGs) we can control their output under any solar irradiance in order to supply real power and positive reactive power, under demand, to the grid and stabilize the grid operation. Furthermore we can supply constant voltage to hydrogen electrolysis units, for an autonomous operation. The efficiencies of FSCPSs with DFIGs can be above 97% of their maximum efficiency [5]. Thus to my opinion DFIGs is an excellent choice for FSCPSs.

2. FSCPS operation equations

The Floating Solar Chimney Power Station (FSCPS) as a whole system is a thermodynamic machine converting solar power to electric power see ref [7]. The produced electric power P_{FSC} depends on various parameters as: The solar irradiance G, the dimensions and characteristic coefficients of its solar collector (D_c,β,tα) and its Floating Solar Chimney (d, H, K, a), the environmental conditions (To, Po) the overall efficiency of the turbines Gear boxes and Generators η_T and the mass flow $\dot{m}$.

As performance characteristic of the FSCPS can be defined the function $P_{FSC}(\upsilon)$ where υ is the inlet air speed in the air Turbines. The performance characteristic of the FSCPS can be derived by the thermal and thermodynamic equations of its parts.

The solar collector thermal equation gives T_{o3} by:

$$T_{o3} = \left[\frac{\tau_{in} a_s G}{\beta + \dot{m} C_p / A_c} \right] + T_o \qquad (1)$$

Where $A_c = \dfrac{\pi \cdot D_c^{\;2}}{4}$ is the solar collector area, tα is the average product of glass transmittance and ground absorptance of solar collector, and β is its average thermal losses coefficient. T_{o3}, $\dot{m}$ and υ are connected by the relations

$$\dot{m} = \rho \cdot \upsilon \cdot A_T \quad (2) \text{ and } \rho = \frac{P_o}{R \cdot T_{o3}} \qquad (3)$$

where: A_T is the overall turbine entrance area.
Combining (1),(2),(3), T_{o3} is given as functions of υ by the relation:

$$T_{o3} = (\sqrt{a_1^{\;2} + 4 \cdot a_2} - a_1)/2 \quad (4) \text{ where:}$$

$$a_1 = \left(P_o \cdot \upsilon \cdot A_t \cdot C_p\right) / \left(R \cdot A_c \cdot \beta\right) - \left(ta \cdot G / \beta + T_o\right) \qquad (5)$$

$$a_2 = \left(P_o \cdot \upsilon \cdot A_t \cdot C_p \cdot T_o\right) / \left(R \cdot A_c \cdot \beta\right) \qquad (6)$$

The temperatures in the various process stages can be derived by the thermodynamic equations relating temperatures and coefficient characteristics as shown in the thermodynamic diagram of fig.2

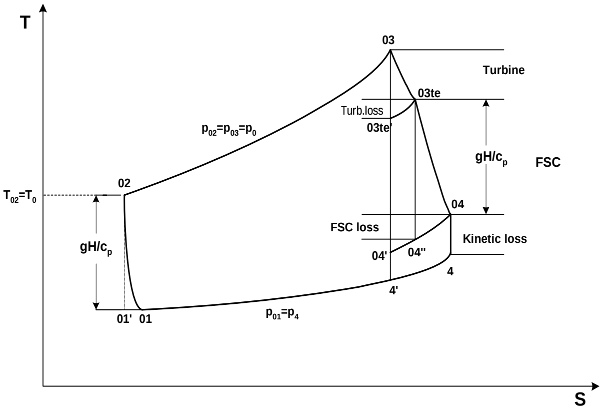

Fig.2

Using these equations we can derive a fourth order polynomial equation

$$w_1 T_4^{\;4} + w_2 T_4^{\;3} + w_3 T_4^{\;2} + w_4 T_4 + w_5 = 0 \qquad (7)$$

where
T4 is the exit air temperature of the FSC. T4 depends through (To3 and $\dot{m}$**)** on the inlet air speed and all the other parameters G, Dc, H, d, K, a, nt, To, Po, ta, b.
Thus the operating equation of the FSCPS is given by

$$P_{FSC}(\upsilon) = C_p \, \dot{m} \cdot \left(T_{o3} - C_1 - T_4 - C_2 \cdot T_4^{\;2}\right) \quad (8)$$

A short presentation of the analysis of ref.[3] is given in appendix I, η_T is assumed constant however this efficiency is a product of three efficiencies.

$$\eta_T = \eta_t \cdot \eta_{mech} \cdot \eta_{el} \qquad (9)$$

η_t is the air turbines efficiency that is function of $\dfrac{\upsilon}{\upsilon_{tip}}$

where υ_{tip} is the turbine blade ends' speed.

η_{mech}, that is function of rotation frequency, is representing friction and windage losses of gear boxes and generators and η_{el}, that is a function of slip of the induction generators, is representing copper iron and harmonics electrical losses.

Approximately we can consider that for large systems η_{mech} is in the range of 0,98, and η_{el} is in the same range. Finally well-designed axial shrouded air turbines can have maximum efficiencies $\eta_{t,\max}$ not less than 0.85.

Hence the maximum expected value for η_T is around 0.8.

3. The operating functions of air turbines

The operating values for air pressure and mass flow of the FSCPSs' define the class of their air turbines, thus axial shrouded air turbines are the appropriate turbines for them.

We assume that N shrouded axial air turbines with horizontal axis, are arranged symmetrically, around the bottom of the solar chimney. Air tending to leave through the FSC has a speed υ, as passes through the overall turbine area $A_t = N \cdot \frac{\pi \cdot d_t^2}{4}$, where d_t is the turbine diameter. For an appropriate FSCPS design the overall turbine area A_t must be smaller than the chimney area $\frac{\pi \cdot d^2}{4}$ in order to secure a smooth diffusing operation for the air turbines.

A shrouded axial air turbine is characterized by its flow coefficient $\Phi = \frac{\upsilon}{\upsilon_{tip}}$ (10) and its load coefficient

$$\Psi = \frac{C_p \cdot (T_{o3} - T'_{o3te})}{\frac{1}{2} \cdot \upsilon_{tip}^2} \quad (11) \quad \text{(see ref.[8])}$$

Where υ_{tip} is the rotational speed of the ends of the turbine blades.

As turbine operating functions usually defined the functions $\Psi(\Phi)$ and $\eta_t(\Phi)$.

These functions are depending among other characteristics, on the blade pitch angle γ and the inlet guiding vanes angle θ. For constant γ and θ, Ψ(Φ), and $\eta_t(\Phi)$ can be defined by measurements or are given by the turbine manufacturer. Using (11) the turbine power is given by:

$$P_t = \frac{1}{2} \cdot \upsilon_{tip}^2 \cdot \Psi \cdot \dot{m} \qquad (12)$$

For usual types of axial turbines $\Psi(\Phi)$ is a linear function of Φ: $\Psi(\Phi) = C_t(\Phi - \Phi_o)$ for $\Phi_o \leq \Phi \leq \Phi_m$

Where: Φ_m is the flow coefficient value that is maximizing $\eta_t(\Phi)$ and Φ_o the zero value of $\eta_t(\Phi)$.

Thus $P_t(\upsilon) = \frac{1}{2} \cdot C_t \cdot \upsilon_{tip}^2 \cdot \left(\Phi - \Phi_o\right) \cdot \dot{m}$ (13)

Typical forms of $\eta_t(\upsilon)$ and $P_t(\upsilon)$ for a given γ and θ are shown in fig (3), for a given value of υ_{tip}

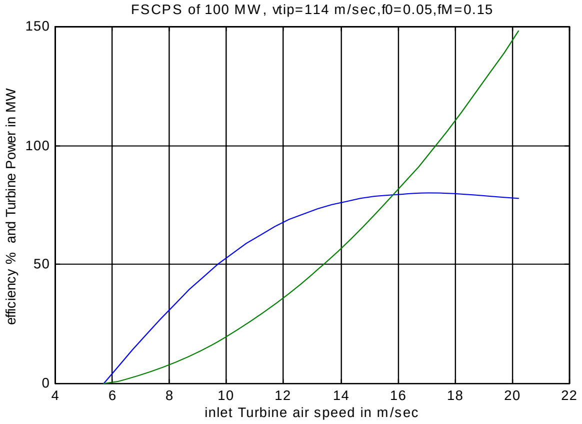

Fig.3

4. The operating functions of Induction generators

As will be shown an excellent choice for FSCPSs are the Doubly Fed Induction Generators (DFIGs).A DFIG is a sophisticated electromechanical converter. It converts the rotational mechanical power P_m that is acting on its rotor, with electrical frequency f_n, to a three phace A.C electrical output power P_{el} with frequency f (f_n is slightly bigger than f).

Usually between the turbine and its respective induction generator a gear box is inserted, with a transmission ratio r. This is necessary in order to match f_n to f. Thus

$$\upsilon_{tip} = \frac{\pi \cdot d_t \cdot f_n}{r \cdot pp} \qquad (14)$$

Where pp is the pole pairs of the generator. The doubly fed induction generator is controlled by a power electronic control unit. This is supplying to its rotor a three phase current under a voltage V_2 and frequency

$$\Delta f = f_n - f. \quad (15)$$

The equivalent electrical circuit per unit of the DFIG is given in fig. (4) where usually the per unit Base values are: the grid frequency f the grid phase voltage V_1 and the rated power of the DFIG P_R.. This P_R is almost equal to the net mechanical power P_m applied to the rotor. Thus the base value for phase current is given by: $P_m / 3\cdot V_1$

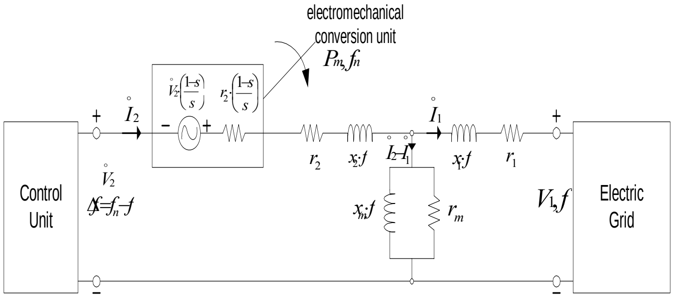

Fig.4

By this circuit it is evident that when $\overset{\circ}{V}_2 = 0$, as in the case of squirrel cage induction generators, the net mechanical power P_m (i.e. the "turbine power P_t minus the mechanical friction and windage losses) is expressed per unit by the relation

$$P_m = \left(\frac{f}{\Delta f}+1\right)\cdot r_2\cdot I_2^2 \quad (16).$$

This is transformed to an output electric power minus the copper, harmonics and iron losses, expressed by

$$P_L = \left(r_2\cdot I_2^2 + r_1\cdot I_1^2 + \frac{V_m^2}{r_m}\right) \quad (17)$$

For its operation the induction generator "absorbs" per unit reactive power given by

$$Q = \left(x_2\cdot f\cdot I_2^2 + x_1\cdot f\cdot I_1^2 + \frac{V_m^2}{x_m\cdot f}\right) \quad (18)$$

For large induction generators with rated electric power P_R the rated P_L is small (about 2% of P_R with another 2% for friction and windage losses). But Q is large usually between 50% and 80% of P_R.

One of the objectives of the power electronic control unit is to supply the DFIG with reactive power for its operation. For FSCPSs with DFIGs this should be the main objective of their control units.

We can prove that the smaller rated power of control units is achieved when V_2 and I_2 are in a phase difference of π/2.

Thus $V_2 = V_2\cdot e^{j\varphi_2}$ and $I_2 = j\cdot I_2\cdot e^{j\varphi_2}$ where φ_2 is their relative phase to output voltageV_1 (that can be received as real).

For this case P_m is given by relation (16) again. The maximum product $V_2\cdot I_2$ is the rated power of the control unit.

By the equivalent per unit circuit of DFIG shown in figure (5) the following complex relationships are derived:

$$\left.\begin{aligned} \frac{V_2\cdot e^{j\varphi}\cdot f_n}{\Delta f} &= j\cdot I_2\cdot e^{j\varphi}\cdot\left(\overset{\circ}{Z}_2+\overset{\circ}{Z}_m\right)-\overset{\circ}{I}_1\cdot\overset{\circ}{Z}_m \\ V_1 &= -\overset{\circ}{I}_1\cdot\left(\overset{\circ}{Z}_1+\overset{\circ}{Z}_m\right)+j\cdot I_2\cdot e^{j\varphi}\cdot\overset{\circ}{Z}_m \end{aligned}\right\} \quad (19)$$

$$\text{where:}\ \left\{\begin{aligned} \overset{\circ}{Z}_2 &= -\frac{f\cdot r_2}{\Delta f} + j\cdot x_2\cdot f \\ \overset{\circ}{Z}_1 &= r_1 + j\cdot x_1\cdot f \\ \overset{\circ}{Z}_m &= \frac{j\cdot x_m\cdot f\cdot r_m}{r_m + j\cdot x_m\cdot f} \\ f &= f_n - \Delta f \end{aligned}\right\} \quad (20)$$

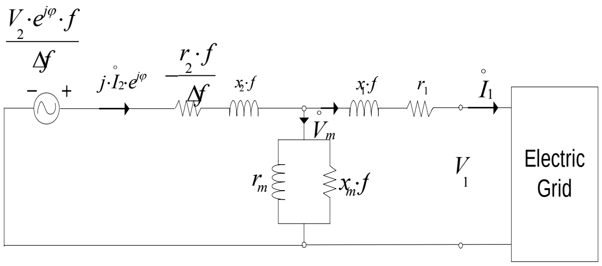

Fig.5

The complex relations (19) and the relation (16) form a system of five real equations with five unknowns for a DFIG connected to the grid with a phase voltage V_1 and frequency f. The unknowns are V_2, φ, I_2 ,$\overset{\circ}{I}_1$. For any given input net mechanical Power P_m with electrical frequency f_n on the rotor, V_2, I_2 , φ, $\overset{\circ}{I}_1$ can be calculated for the DFIG connected to a grid with V_1 and f.

For autonomous power production by the FSCPS, for hydrogen electrolysis, that demands a constant voltage V_1, and absorbs a zero phase current I_1, the five unknowns are: Δf, V_2, I_2 , φ, I_1 .

It can be proved, in this case, that f is not constant, if we intent to produce, for any solar irradiance G, its respective maximum electric power. However in electrolysis we convert AC to DC, thus the variation of f has no effect to the electrolysis procedure.

5. Rated operation of the FSCPS

As rated operation for the FSCPS we can define the operation that is under the average solar irradiance G_{av} and maximum efficiency $\eta_{t,\max}$. Assuming that the inlet air speed in the turbines for this operation is υ_m, this speed can be calculated by the operational function of the FSCPS as the value of υ maximizing the P_{FSC} for G_{av}. The efficiency η_t becomes maximum for a certain flow coefficient Φ_m. Thus the operating υ_{tip} for rated power production by the FSCPS is equal to υ_m/Φ_m.

The rated power of the turbines and generators should be at least 25% bigger than the rated power of the FSCPS in order to produce its maximum rated power under maximum solar irradiance G_{max} that usually is received as 25% bigger than G_{av}.

6. Operation of FSCPS with squirrel cage induction generators under variable G

Let us consider that the N cage induction generators of the FSCPS are connected to the same electric grid, with constant phase voltage V_1 and frequency f. The operating slip s of their operation can define f_n by the relation $f_n = f\cdot(1+|s|)$ (21) , and thus the υ_{tip} by the relation (14). However $|s| \prec 0.01$. Thus as a first choice f_n is considered approximately equal to f. The intersection between the operating function of the FSCPS $P_{FSC}(\upsilon,\eta_t(\upsilon/\upsilon_{tip}),G)$ and the operating function of N turbines $N\cdot P_t(\upsilon/\upsilon_{tip})$ defines the operating point i.e the inlet air speed in the turbines and the produced output power P_t, by each axial turbine.

The net mechanical output of each turbine i.e. P_t minus (friction and windage losses) = P_m, is the input mechanical power to its induction generator. This mechanical net power is transformed to output electric power that is equal to P_{el} = P_m – (copper, iron and harmonic losses) and can be easily calculated by the equivalent circuit of fig.(5) for V_2=0. This electric power it will be supplied under a slip $|s| = \dfrac{\Delta f}{f}$ defined by the electric generator equations. Thus f_n is redefined by the relation $f_n = f\cdot(1+|s|)$ Thus υ_{tip} is redefined more accurately. Using the new value of υ_{tip} and following the previous procedure of calculations $|s|$ is redefined. After two to three steps P, and s can be calculated with an excellent accuracy for engineering applications.

In figure (6) the intersection of $N\cdot P_t(\upsilon/\upsilon_{tip})$ and $P_{FSC}(\upsilon,\eta_t(\upsilon/\upsilon_{tip}),G)$ for variable G are given for a FSCPS of 100MW for G_{av} = 800 W/m^2 and G_{max}=1000 W/m^2 , with rated power for turbines and generators 127 MW in order to encounter the operation under maximum solar irradiance.

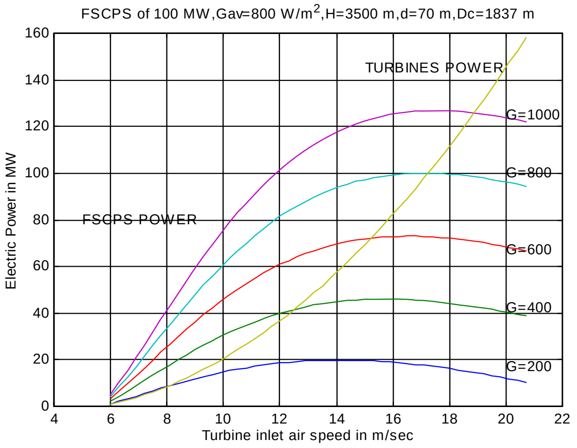

Fig.6

In figure (7) the produced power by the induction generators is shown, as function of the solar irradiance G, together with the maximum Power of the FSCPS for the same G.

The dimensions and characteristics of the FSCPS are:
D_c=1837 m, d=70 m, H=3500 m, K=1.5, α=1.1058,
T_o=303.2°K, P_o=101300 Pa, β=5.75 W/m^2 °K, tα=0.75

The efficiency function $\eta_T(\Phi)$ is considered as approximately given by the following equation:

$$\eta_T(\Phi) = \eta_{T,\max}\cdot\frac{2\cdot(\Phi_m-\Phi_o)\cdot(\Phi-\Phi_o)}{(\Phi_m-\Phi_o)^2+(\Phi-\Phi_o)^2} \qquad (22)$$

For the present case Φ_0=0.05 and Φ_m=0.15.

The squirrel cage induction generators have the following per unit values r_1=r_2=0.01, x_1=x_2=0.1, r_m=500, x_m=3.

The reactive power that is “absorbed” by the grid is shown also for every G.

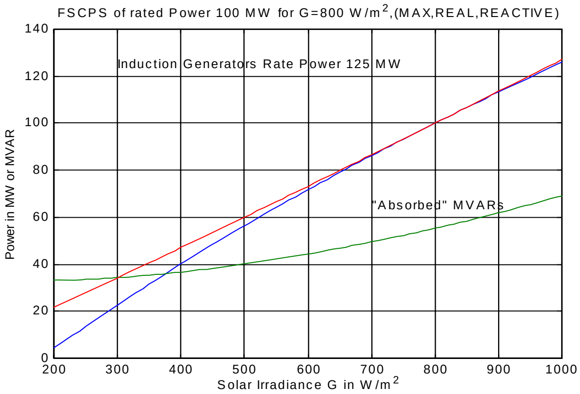

Fig.7

As it is obvious using squirrel cage induction generators almost the maximum power is produced at least for solar irradiances near $G_{av.}$ For G lower than 600 W/m^2 the power is obviously smaller than the respective $P_{\max}$. In order to increase the efficiency, for low values of solar irradiance G, we can operate only a part of the air turbines and shut down the entrance of the non-operating units. By this technique the annual efficiency of the FSCPS with induction generators will not be less than 97% of the maximum annual energy of the FSCPS.

However the problem of stability and reactive power absorption can be solved only using DFIGs instead of squirrel cage induction generators.

7. The rated power of the electronic control unit

Let us now consider that we control the D.F.I.Gs in order to supply reactive power to the grid under φ_1 (φ_1 is the phase value of $\overset{\circ}{I}_1$). The real power and the reactive power per unit supplied to the grid are $I_1 \cdot \cos\phi$, $I_1 \cdot \sin\phi$ respectively.

The maximum real power $P_{\max}$ supplied by the DFIGs to the grid it will be produced under $G_{\max}$. Thus V_2 should be the appropriate value, in order to be supplied to the grid the maximum electric real power $P_{\max}$ and positive reactive power equal to $Q = P_{\max} \cdot \tan\varphi_1$, under the constraint that $\overset{\circ}{V}_2 \wedge \overset{\circ}{I}_2 = \pi/2$. (23)

Thus for a given constant per phase per unit voltage $V_1=1$ the per phase per unit current should be $\overset{\circ}{I}_1 = I_1 \cdot e^{j\varphi_1}$ and $\overset{\circ}{V}_2 = V_2 \cdot e^{j\varphi}$, $\overset{\circ}{I}_2 = j \cdot I_2 \cdot e^{j\varphi}$.

The operating slip of the DFIGs is always negative, i.e. the DFIGs are working in over synchronous mode.

Let us consider that P_m, V_1, f are the base values for the per unit system, thus: $P_m=1$, $V_1=1$, $f=1$. By (16)

$$P_m = \frac{I_2^2 \cdot r_2 \cdot (f+\Delta f)}{\Delta f} = I_2^2 \cdot r_2 \cdot \left[\frac{1}{\Delta f} + 1\right] \quad (24)$$

For a given φ_1, the complex equations (19) are equivalent to four real relationships. These combined with equation (24) are equivalent to five real equations with unknowns I_2, V_2, φ, I_1, Δf.

By this system for a given φ_1, the per unit values of V_2, I_2 can be calculated. The product $V_2 \cdot I_2$ defines the per unit rated power of the electronic control unit. As an example for given values of r_1, r_2, x_1, x_2, r_m, x_m as in previous paragraph, $V_2 \cdot I_2$ was calculated as function of φ_1. Using these results, the rated power of the control unit is shown in fig(8) as function of the $\tan\varphi_1$.

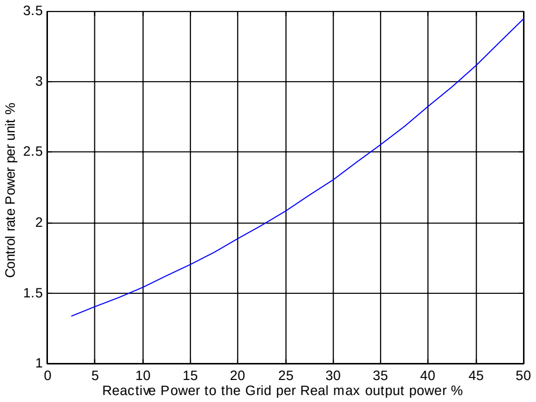

Fig.8

By this figure is evident that in order to supply the grid with positive reactive power 50% of $P_{\max}$, a small control unit with rated power 3.5% of $P_{\max}$ is enough.

8. Annual efficiency by FSCPSs with Induction generators

The maximum output power by the FSCPSs is almost proportional to solar irradiance G. Thus the maximum annual average power is the maximum output power under G_{av}.

Thus it can be proved that the annual efficiency is equal to $\eta_o = 1.07 \cdot \frac{P_{\max}(G_{av})}{A_c \cdot G_{av}}$. (25) (see ref [5])

The coefficient 1.07 is related with stored energy and night operation as was shown in ref.[5].

However in case of FSCPSs with Induction generators connected straightforward to the electric grid, with constant frequency f, this efficiency is smaller. The induction generators rotate with almost constant electric frequency f_n, thus υ_{tip} is approximately constant for any G. For varying inlet air speeds to the air turbines due to varying solar irradiance G, the efficiencies are varying (i.e. are not maximum for every G), thus the air turbines produce less than their respective maximum energy. Thus the annual efficiency η_o' is smaller than η_o. Under reasonable estimations we can prove that $0.95 \cdot \eta_o \le \eta_o' \le \eta_o$. Furthermore for lower G values, we can operate a smaller number of turbines, thus we can increase even more the operating efficiency hence as an average $\eta_o' \cong 1.04 \cdot \frac{P_{\max}(G_{av})}{A_c \cdot G_{av}}$. (26)

Hence DFIGs are not necessary in order to increase the annual efficiency as in wind power applications.

The use of DFIGs is related mainly with their ability to supply, under demand, positive reactive power to the grid. Another useful property of DFIGs is the regulation of their output by the control unit. This property can be used in order to stabilize the FSCPSs operation under any grid instabilities.

In case of hydrogen production by electrolysis by the previous FSCPSs, the DFIGs can be controlled in order to supply constant voltage output under maximum power production. In fig.(9) the electrolysis per unit output power as function of solar irradiance and respective per unit variable output frequency, for constant voltage and maximum power output for the previous FSCPS of 100 MW are given. This operation can be achieved with the appropriate control supply (V_2, Δf) for every G shown in fig.(10).

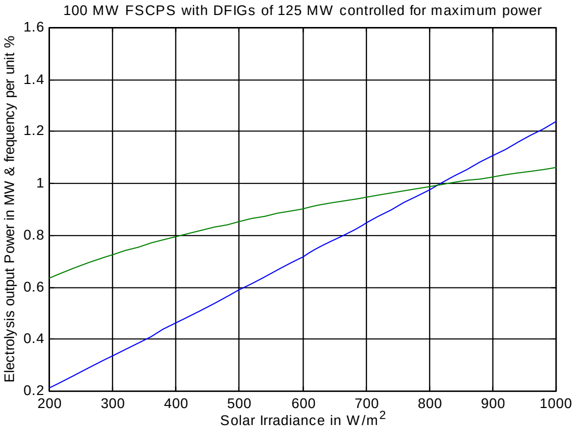

Fig.9

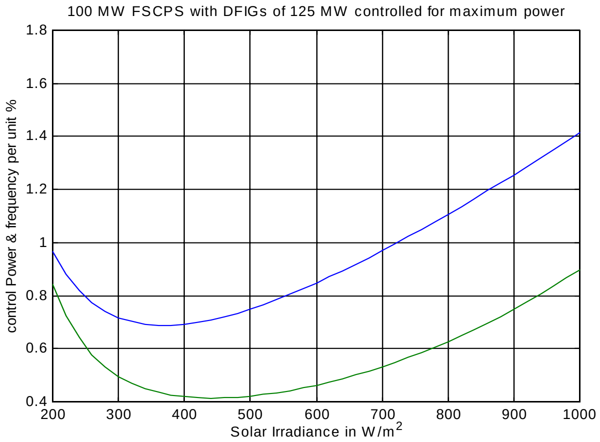

Fig.10

As already mentioned the deviation of output frequency has no effect on electrolysis procedure, because the output AC is converted to DC. In this case the annual efficiencies can be equal to η_o. Thus using DFIGs as electric generators for FSCPSs we can simultaneously supply power to a grid or produce hydrogen and oxygen by electrolysis. This property is very important especially in relation to H_yO_x engine technology [10].

9. Conclusions

The appropriate air turbines for FSCPSs are the axial shrouded air turbines. These turbines are occupied with inlet guiding vanes and appropriate exit diffusers.

The DFIGs are an excellent choice for the electric generators for the FSCPSs. The DFIGs for this application are occupied with small power electronic control units, with rated power not exceeding 3.5% of their generators power. These DFIGs can control the FSCPSs reactive power output supplied to the grid, up to 50% of their real power. The real power supplied to the grid is almost the maximum for any G near G_{av}. FSCPSs using DFIGs, have annual efficiencies not less than $1.04\cdot\frac{P_{\max}(G_{av})}{A_c\cdot G}$. Using DFIGs, the FSCPSs can supply to the grid positive reactive power, under demand, and stabilize their operation under grid instabilities.

The FSCPSs with DFIGs can be used for hydrogen production by electrolysis. In this case their efficiencies can be maximized, because the DFIGs could be controlled in order to operate for any solar irradiance with maximum power production.

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Appendix I

In the Appendix the equations for a FSCPS are given as was presented in ref. [3]. The FSCPS has a thermodynamic cycle shown in fig. (2).

A. Nomeclature

α – kinetic energy correction coefficient
A_c – solar collector surface area
A_t – inlet turbine surface area
β – solar collector average thermal loss coefficient
C_p – isobaric specific heat = 1005 Joule/Kg·°K
d – internal FSC diameter in m
D_c – solar collector diameter in m
g – gravity constant = 9.81 m/sec^2
G – solar irradiance in W/m^2
H – FSC height in m
k – FSC friction loss coefficient
$\dot{m}$ – mass air flow in Kg/sec
η_t – turbines efficiency
η_T – turbines and generators efficiency
$p_0 = p_{02} = p_{03}$ –stagnation air pressure in the solar collector
p_0 – environmental pressure in the entrance of solar collector
p_4 – static air pressure in the exit of the FSC
P_{FSC} – FSCPS's electric power output
P_T – turbine electric power output
P_t – mechanical turbine output
R – air constant = 287 Joule/Kg·°K
tα – average transmittance × absorptance coefficient
$T_{02} = T_0$ – environmental temperature in the entrance of solar collector
T_{03} – Temperature at the exit of solar collector that is the entry temperature of the air in the air turbines
T_{03te} – warm air exit stagnation temperature from the air turbines
T'_{03te} - isentropic exit stagnation temperature from the air turbines
T_{04} – stagnation air temperature in the exit of the FSC
T_4 – static air temperature in the exit of the FSC
T'_4 – isentropic static air temperature in the exit of the FSC
T_{01} – stagnation temperature in the output altitude of the FSC
T'_{01} – stagnation isentropic temperature in the output altitude of the FSC
υ_{exit} – air speed in the exit of FSC
υ – inlet air speed in the turbines

B. The Equations

$T_{o3} = \left[\dfrac{\tau_{in} a_s G}{\beta + \dot{m} C_p / A_c} \right] + T_o$ by the solar collector thermal equation

$$T'_4 = T_{03} \left(1 - \frac{gH}{C_p T_o} \right)$$

$$p_4 = p_o \left[1 - \left(\frac{gH}{C_p T_o} \right) \right]^{3.5}$$

by the thermodynamic cycle (fig.2) for isentropic processes between isobarics

$$w_1 T_4{}^4 + w_2 T_4{}^3 + w_3 T_4{}^2 + w_4 T_4 + w_5 = 0$$

where w_1, w_2, w_3, w_4, w_5 are given by the relations

$$w_1 = C_2{}^2 (1 - k)$$
$$w_2 = C_2 \left(2 - k - n_T C_2 T_4{}' \right)$$
$$w_3 = C_2 C_3 \left(1 - k \right) + 1 - 2 n_T C_2 T_4{}'$$
$$w_4 = C_3 - n_T T_4{}' \left(1 + C_1 C_2 \right)$$
$$w_5 = -n_T T_4{}' C_1$$

where

$$C_1 = \frac{gH}{C_p}$$

$$C_2 = \frac{a}{2C_p} \left(\frac{R\dot{m}}{\left(\pi \frac{d^2}{4} \right) p_4} \right)^2$$

$$C_3 = T_{o3} \left(n_T - 1 \right) + C_1$$

T_4 is the real root of the fourth order polynomial equation near to T'_4

$$P_{FSC} = \dot{m} C_p \left(T_{o3} - T_{o3te} \right)$$

where $T_{o3te} = T_4 + C_1 + C_2 T_4{}^2$

$$\upsilon_{exit} = \frac{\dot{m}}{\rho A} = \frac{\dot{m} R T_4}{A p_4}$$