

Floating Solar Chimney Power Stations with Induction Generators

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Key Words

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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 1.5÷3.5 Km giving to their respective power stations efficiencies from 1.5÷5%. The axial shrouded air turbines of the FSCPSs are geared to appropriate electric generators. In the present paper the squirrel cage induction generators are examined as a simple and economical solution for connection of FSCPSs straight forward to the grid. Due to the FSCPSs characteristics it will be proved that at least 97% of the theoretically maximum production energy by the FSCPS can be supplied to the grid when squirrel cage induction generators are used.

Introduction

The solar chimney power stations were invented by prof. J. Schlaigh (1995). In his book, Schlaigh gives an extensive presentation for them. A solar chimney power station is mainly a set of three components:

- A large cyclical solar collector of external diameter D_c
- A tall solar chimney in its center with internal diameter d and height H
- A set of air turbo generators near the bottom of the solar chimney

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

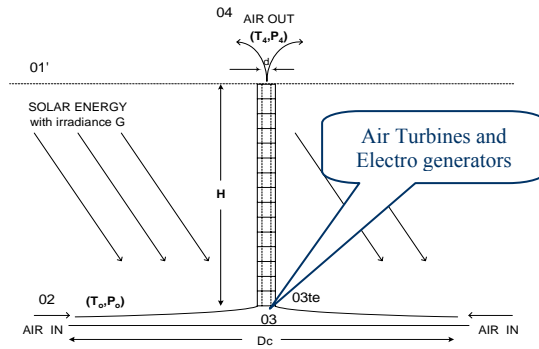


Figure 1. Indicative operation diagram of the FSCPS

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.

In a set of related papers (Papageorgiou C., 2004) proposed solar chimneys as lighter than air structures, made by light enduring fabric, used in balloon and airship industry. These structures believes that can float in the air and were named floating solar chimneys (FSCs), can encounter effectively the operational sub pressure and the external winds. As it has been proved the efficiencies of STPSs with FSCs, with heights H in the range of 1.5 km to 3.5 km, are in the range of 1.5% to 5%, including night operation and stored energy effects.

The experience and know-how by constructing STPSs with FSCs, will give the opportunity, in the near future, to operate such solar power stations, made by advanced composite materials, that will have construction costs per rated KW in the order of 500 USD, with annual power productions not less than 3000 KWh per rated KW.

In the present paper the STPS connected to the electric grid with squirrel cage induction generators is examined. The squirrel cage induction generators are very simple in operation with minimum cost and maintenance. The electric grid defines their frequency hence their angular speed is practically constant around their synchronous angular speed for the grid frequency.

The operation Function for the STPSs

The STPS indicative operation as shown fig.1 has a respective thermodynamic cycle shown in fig.2, as presented by Cannon and Backstrom (2000).

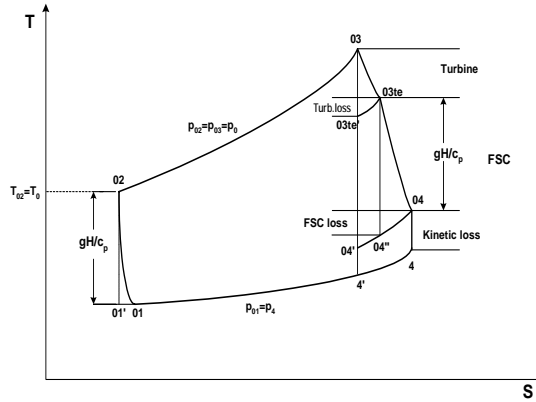


Figure 2. Thermodynamic cycle of the FSCPS

Using the energy and thermodynamic equations derived by this diagram, Papageorgiou (2004) gave an analytic equation describing the operation of the STPS.

A short presentation of this analysis is given in Appendix 1.

The main results are the following :

The electric power output P_{FSC} , is related to a mass flow \dot{m} by the relation

$$P_{FSC} = C_p \dot{m} (T_{o3} - C_1 - T_4 - C_2 \cdot T_4^2) \quad (1)$$

Where T_{o3} is the entrance stagnation air temperature in the airturbine. T_{o3} can be defined exclusively by the solar collector dimensions and thermal parameters, the solar irradiance G , the environmental temperature T_o and the mass flow \dot{m} . An approximate formula for T_{o3} , is given in Appendix 1.

$$T_4 \text{ is the appropriate root of fourth order polynomial equation: } w_1 T_4^4 + w_2 T_4^3 + w_3 T_4^2 + w_4 T_4 + w_5 = 0 \quad (2)$$

where w_1, w_2, w_3, w_4, w_5 as C_1 and C_2 are functions of dimensions and parameters of solar chimney (d, H, k, α), the environmental temperature T_o and pressure P_o and the efficiency η_T of the turbines and generators and the mass flow \dot{m} .

For a given STPS and constants T_o, P_o , the varying parameters are \dot{m} , G and η_T .

The mass flow \dot{m} can determine the inlet air speed v in the turbines. In fact let us assume that the STPS has N

turbines each one with diameter d_t . The mass flow will pass through a surface area A_t given by $N \cdot \frac{\pi \cdot d_t^2}{4} = A_t$

(3)

The chimney area $\frac{\pi \cdot d^2}{4}$ should be bigger than A_t for the appropriate operation of the air turbine diffusers.

It is evident that $\dot{m} = \rho \cdot A_t \cdot v$, where ρ can be calculated approximately by the formula $\rho = \frac{P_o}{R \cdot T_{o3}}$,

hence v is given by the equation $v = \frac{\dot{m} \cdot R \cdot T_{o3}}{P_o \cdot A_t}$ (4)

Thus the output electric power P_{FSC} of the FSCPS is a function of the inlet air speed v in the air turbines, the solar irradiance G and the overall efficiency of the turbines, gearboxes, and electric generators η_T .

($\eta_T = \eta_t \cdot \eta_{gear} \cdot \eta_{gen}$), i.e. $P_{FSC} = P_{FSC}(v, G, \eta_T)$ (5)

The electric power output P_{FSC} can be plotted against v . In figure (3) a set of power curves are shown for variable solar irradiance $G=200-1000$ w/m² and $\eta_T=0.8$, for a FSCPS of 100 MW. The FSC has height $H=3500$ m and internal diameter $d=70$ m. The solar collector diameter is $D_c=1837$ m and the turbine inlet surface $A_t=2463$ m².

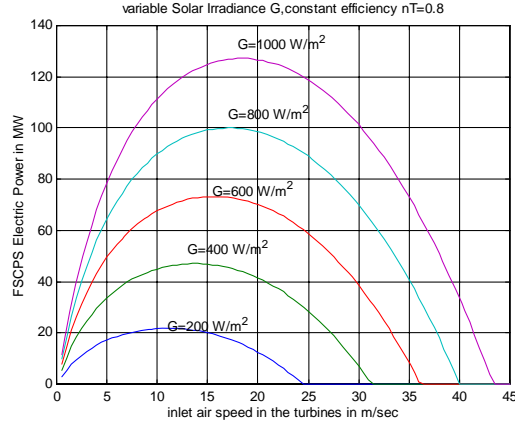


Figure 3. Power output as function of the inlet air speed in the air turbines of the FSCPS

We can notice that the optimum inlet air speed is varying from 18.4 m/sec for $G_{\max}=1000\text{W/m}^2$ to 11m/sec for $G_{\min}=200\text{W/m}^2$. This is a characteristic of the FSCPSs. In the following paragraphs we will see how we can maximize the power output using the operational properties of induction generators.

The air turbine functions of operation

The appropriate air turbines for STPSs are the axial shrouded air turbines.

The turbines transform part of the thermo kinetic energy of moving air stream towards the bottom of the solar chimney to rotational power output P_t . This finally through appropriate gear boxes and electric generators is transformed to electric power output $P_T = P_t \cdot \eta_{gear} \cdot \eta_{gen}$ where η_{gear} , η_{gen} are the efficiencies of gearbox and

electric generators. Considering η_{gear} and η_{gen} constants in the range of operation P_T and P_t are proportional.

The operation of a given air turbine is described by two functions, relating the following characteristics: flow

coefficient $\Phi = \frac{v}{v_{tip}}$, load coefficient Ψ and efficiency η_t , where Ψ is defined by the equation

$$\Psi = \frac{C_p \cdot (T_{o3} - T_{o3te})}{\frac{1}{2} \cdot v_{tip}^2} \quad (6) \text{ and } v_{tip} \text{ is the rotational speed of the ends of the blades of the air turbines.}$$

The operation functions of the air turbines are the functions $\eta_t(\Phi)$ and $\Psi(\Phi)$. $\Psi(\Phi)$ can be transformed to the function

$P_t(\Phi)$, taking into consideration that $C_p \cdot (T_{o3} - T_{o3te}) \cdot \dot{m} = P_t$ and $\dot{m} = \rho \cdot A_t \cdot v = \rho \cdot A_t \cdot v_{tip} \cdot \Phi$

$$\text{Thus } P_t(\Phi) = \left[\frac{1}{2} \cdot \rho \cdot v_{tip}^3 \cdot A_t \right] \cdot \Phi \cdot \Psi(\Phi) \text{ and } P_T(\Phi) = \left[\frac{1}{2} \cdot \rho \cdot v_{tip}^3 \cdot A_t \right] \cdot \Phi \cdot \Psi(\Phi) \cdot \eta_{gear} \cdot \eta_{gen} \quad (7)$$

The functions $\eta_t(\Phi)$ and $P_T(\Phi)$ for a given axial shrouded air turbine are depending on: the blade pitch angle (γ) and the inlet guiding vanes flap angle (θ).

The variations of these angles strongly effects the efficiency of the functions $\eta_t(\Phi)$ and $P_T(\Phi)$, see for example Gannon A., Von Backstrom T. (2003).

In the present paper γ , θ will be considered as constants thus the functions $\eta_t(\Phi)$ and $P_T(\Phi)$ are defined.

The operation of the FSCPS is regulated automatically through its induction generators.

The induction generator operation

The induction generator's electric power output, can be given by the relation, presented by Siegfried (1998):

$$P(s) = \frac{2 \cdot P_k \cdot (1 - s)}{\left(\frac{s}{s_k} + \frac{s_k}{s} \right) \cdot (1 - s_k)} \quad (8)$$

The slips s and s_k for the squirrel cage induction generators are always negative.

P_k is the power for maximum net torque applied to the axis of the generator and achieved for $s=s_k$. The rated power output of induction generators is usually $P_r=(0.3\div 0.5) \cdot P_k$. This means practically that the rated slip s_r is in the range

of $(0.15\div 0.25) \cdot s_k$. It can be proved that for large induction generators $\left| s_r \right| < 1\%$.

The losses of the induction generator are the primary and secondary copper losses, iron losses, harmonics losses and wintage and friction losses. These losses can be considered that (in the range of operation) are constant and not more than 4% for a large induction generator.

Between the axial air turbine of the STPSs and their induction generators usually are inserted appropriate gear boxes. These are necessary in order to convert the rotational power output of the axial air turbines in order to match the induction generators with the grid frequency.

The gearboxes can be avoided only if we increase the number of pole pairs of the induction generators but in general this is not the best techno economical decision. Gear boxes are characterized their transmitted ratio r and their efficiency η_{gear} .

The turbine blades' ends speeds is given by the relation
$$v_{tip} = (1 + |s|) \cdot \frac{\pi \cdot f \cdot d_t}{r \cdot pp} \quad (9)$$

Where d_t is the diameter of the air turbines and pp the pole pairs of the generator.

Thus v_{tip} is defined by the induction generator slip s and the grid frequency f .

The rated operation of the air turbines and electric generators

The electric power output of the FSCPS is defined by the intersection of the independent functions

$P_{FSC}(v, G, \eta_T(\Phi))$ and $P_T(\Phi)$ where $\eta_T(\Phi)$ is a given function of Φ .

As rated operation for turbines and the generators it is defined the operation, under G_{max} , where the maximum power output P_{max} , is achieved. Hence $\eta_T(\Phi)$, must also be maximum. The maximum of the function $\eta_T(\Phi)$ defines Φ_m

and $\eta_{T,\text{max}}$. The maximum of the function P_{FSC} , with $\eta_{T,\text{max}}$ and G_{max} defines v_m for which $P_{FSC}=P_{\text{max}}$.

Then $v_{tip,m}$ is defined by the relation
$$v_{tip,m} = \frac{v_m}{\Phi_m}$$

The induction generators supply to the grid their rated power equal to P_{max} for their rated slip s_r .

The axial turbines for Φ_m , will produce through their geared electric generators power $P_T=P_{\text{max}}$.

The gearboxes transmission ratio r is calculated through the relation (9) for $s=s_r$.

For G smaller than G_{\max} in order to find the operation point we proceed as follows:

As a first step, v_{tip} is received equal to $v_{tip,m}$. The intersection of functions $P_{FSC}(v)$ and $P_T(v)$ gives the point of operation for the given G and $v_{tip,m}$, i.e. gives the electric power output and the inlet air v speed in the turbines. As a second step through the induction generator equation we can define more accurately the s and thus v_{tip} is redefined by the relation (9). Through the new value of v_{tip} , the operation point is redefined as a new intersection point etc. With 2 to 3 steps the achieved accuracy is excellent for engineering applications.

Application for a FSCPS of 100 MW

In order to apply the previous analysis $\eta_t(\Phi)$ and $P_T(\Phi)$ must be known for a FSCPS, with known $P_{FSC}(v, G, \eta_T(\Phi))$. As an approximation, $\eta_T(\Phi) \cong 0,96 \cdot \eta_t(\Phi)$.

Taking into consideration the forms of the functions $\eta_t(\Phi)$, $P_T(\Phi)$ as given by related books and papers and as an example we can consider for constant blade pitch angle γ and inlet guiding vanes angle θ , these functions as follows:

$$\eta_T(\Phi) \cong \frac{1.6 \cdot (10 \cdot \Phi - 0.5)}{1 + (10 \cdot \Phi - 0.5)^2} \quad (10)$$

That gives, $\eta_T = 0$ for $\Phi = 0.05$ and $\eta_{T,\max} = 0.8$ for $\Phi_m = 0.15$

$P_T(\Phi)$ can be considered as the appropriate curve passing through the points

$P_T = P_{\max}$, $\Phi_m = 0.15$ and $P_T = 0$, $\Phi = 0.05$.

The form of this curve depends on the dimensions and specific characteristics of the shrouded air turbines.

As an approximation we can consider that $P_T(\Phi) = P_{\max} \cdot (10 \cdot \Phi - 0.5)^\ell$

As an average $\ell = 1.5$ is a reasonable choice. Thus $P_T(\Phi) = P_{\max} \cdot (10 \cdot \Phi - 0.5)^{1.5}$ (11)

The electric generator equation is given by $P_{Gen}(s) = \frac{C \cdot P_{\max} \cdot (1 - s)}{\frac{s}{s_k} + \frac{s_k}{s}}$ (12) where we have received

$s_k = -0.05$ and $s_r = -0.01$, $C = 0.1904$.

The FSCPS has a maximum power $P_{\max}=127$ MW for $G_{\max}=1000$ W/m² and the following dimensions and constants $d=70$ m, $H=3500$ m, $D_c=1837$ m, $K=1.5$, $\alpha=1.1058$, $T_o=303.2^\circ\text{K}$, $P_o=101300$ Pa, $b=5.75$ W/m² °K, $\tau\alpha=0.75$ and thirty six shrouded air turbines with overall inlet surface area =2463 m² and thirty six induction generators with rated power 3.5 MW.

The average solar irradiance $G_{av}=800$ W/m² defines the rated power of the FSCPS to 100 MW.

Following the previous analysis we can calculate the output electric power as function of the solar irradiance G , for $200 \leq G \leq 1000$. This function is shown in figure (4), together with the $P_{\max}(G)$, that is the maximum power that could be produced by the FSCPS for constant $\eta_T=0.8$.

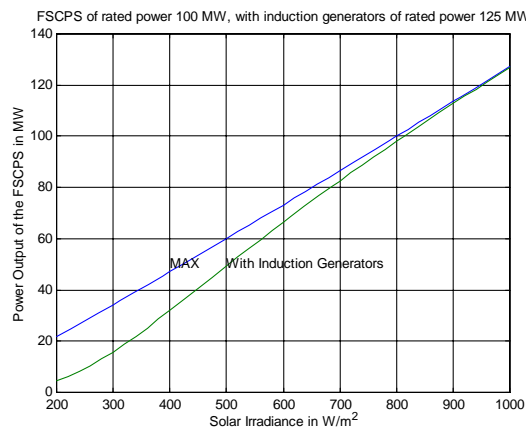


Figure 4. Maximum power output of the FSCPS as function of the horizontal solar irradiance

As it is evident almost the maximum power is extracted by the FSCPS for solar irradiance G between 600÷1000 W/m². In this case the variation in power is 80%. If thermal storage is used on the ground of the solar collector (by plastic bags or closed tubes filled with water for example) then the daily operation it does not follows the solar irradiance variations but is much more smooth. Equivalently we could say that the respective variation can be only 5%÷20%. Thus using thermal storage and induction generators practically the maximum energy per day should be produced, with an appropriate choice of air turbines and electric generators. In winter, the power is obviously smaller than in the summer. In order to increase the efficiency for the average lower values of solar irradiance G in the winter, 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.

The maximum annual efficiency is given approximately by $\eta_o = \frac{1.07 \cdot P_{\max}(G_{av})}{G_{av} \cdot A_C}$, where A_c is solar collector area.

Thus as an approximate formula for the average annual efficiencies of FSCPSs, with conventional squirrel cage induction generators is the following $\eta_o = 1.04 \cdot \frac{P_{\max}(G_{av})}{G_{av} \cdot A_C}$. (13)

Conclusions

The steady state operation of FSCPS with squirrel cage induction generators connected to the grid was examined. Using appropriate designed shrouded air turbines it is possible to produce annually at least 95% of the theoretically calculated maximum electric energy. This is achieved due to the smoother and smaller range of air speed changes inside the FSCPS compared to the wind turbines. In any case under reasonable assumptions, well-designed and carefully tuned shrouded air turbines for the FSCPSs and squirrel cage induction generators connected to the grid is a good and economical choice. The disadvantages of using squirrel cage induction generators are:

- The generators ‘‘absorb’’ reactive power by the grid
- There is no control on them, that in certain cases is critical under grid instabilities

These problems can be solved using Doubly Fed Induction Generators (DFIGs) instead of Squirrel Caged Induction Generators. With their electronic control, we can operate and stabilize DFIGs as zero or positive producing reactive power sources when necessary.

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. Nomenclature

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 \cdot °K

d – internal FSC diameter in m

D_c – solar collector diameter in m

g – gravity constant = 9.81 m/sec²

G – solar irradiance on horizontal surface in W/m²

H – FSC height in m

k – FSC friction loss coefficient

\dot{m} – mass air flow in Kg/sec

η_i – 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 \cdot °K

$\tau\alpha$ – average transmissivity \times absorssivity 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

v_{exit} – air speed in the exit of FSC

v – inlet air speed in the turbines

B. The Equations

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

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

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

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

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

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

$$w_1 = C_2^2 (1 - k)$$

$$w_2 = C_2 (2 - k - n_T C_2 T_4')$$

$$w_3 = C_2 C_3 (1 - k) + 1 - 2n_T C_2 T_4'$$

$$w_4 = C_3 - n_T T_4' (1 + C_1 C_2)$$

$$w_5 = -n_T T_4' C_1$$

where

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

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

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

T_4 is the real root of the fourth order polynomial equation near to T_4

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

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

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

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