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An Isolated Hybrid Fuzzy Controlled-Photovoltaic Diesel-PMSG System

Noureddine Hidouri[1] Lassâad Sbita[2] and Taoufik Mhamdi[3]

[1]noureddine.hidouri@yahoo.fr, [2]lassaad.sbita@enig.rnu.tn, [3]mhamdi_taoufik@yahoo.com,

Research Unit of Photovoltaic, Wind turbine and Geothermal Systems

National Engineering School of Gabes, Tunisia

Abstract— **in this paper, a hybrid photovoltaic-diesel system control is presented. The considered system is composed of two generators; a photovoltaic array and a permanent magnet synchronous generator (PMSG). The adequate choose between the generators is controlled by a fuzzy supervisor in order to fed the considered load according to power demand. In order to feed the isolated load when the PV array is insufficient, a PMSG driven by a diesel motor is used and a diode rectifier and an LC-LC filter are associated to the PMSG. Thus, in this case, the load is fed by both the PMSG and the photovoltaic panel. In the other case, when the PV array power is sufficient, the load receives the input power only from the photovoltaic array through a boost converter and a DC bus. An important simulation work was performed in order to take out the considerable results. To confirm the high system performances, presented results are discussed and show how the proposed methodology is an efficient hybrid photovoltaic diesel control procedure.**

Keywords—**Hybrid isolated system, Photovoltaic, Diesel, PMSG, Boost converter, Fuzzy control.**

I. Introduction

Supplying continuously the competitive needed electrical energy is an important factor for the human societies and the technologies development.

Stand alone energy generation is needed in the islands, the mountains and the isolated grid power areas. The use of mix energy such as photovoltaic and wind or photovoltaic and diesel is a better solution [1], [2].

Due to its clean and renewable nature, photovoltaic is becoming the most important renewable energy source in the world. It offers many advantages such as emitting no noise, not being polluting, requiring little maintenance, and but the output power varies randomly due to fluctuation of solar insulation and climatic conditions. It completely disappears during the night hours. There must be a stand by power source to meet the load energy demand. Diesel engine driven generator are the most common electrical energy production scheme in small and medium size power application is used to provide an uninterrupted energy sources in remote area, it works as a compensator to the fluctuating power output of the photovoltaic array (PVA) [3],[4] .That's why the design of hybrid power system has received considerable attention. It may constitute economical solution in many applications, and provide more reliable supply of electricity through the combination of several energy sources.

Squired-cage Induction generator [7], [9] and Synchronous Generator with external field excitation are associated with a Diesel engine drive a generator to produce electricity. In this paper a permanent magnet synchronous generator is coupled to the diesel engine. In order to stabilize the magnitude and the voltage frequency, the speed of the diesel engine is controlled. To make possible the connections of diverse energy sources [3], the design process of hybrid energy systems requires the management and the selection of the most suitable combination of energy sources. Thus in this paper a fuzzy supervisor is used to select the suitable energy source when the load varies.

II. THE HYBRID SYSTEM MODEL

Taking into account works published in [8], [9], the proposed hybrid system considered in this work is shown in fig. 1.

The rotor of the PMSG is coupled to the diesel motor in order to convert the mechanical power to electrical power required by the considered load.

The obtained three phase stator voltage are rectified by a three phase full bridge diode rectifier and filtered by an LCLC filter, so that a smooth required DC load voltage can be obtained and the fluctuation voltage will be suppressed.

In the other way, the DC load can be fed also by a DC voltage provided only by the PV panel through the PWM boost converter. A fuzzy supervisor is used in this hybrid configuration to take decision about the choice between the two ways.

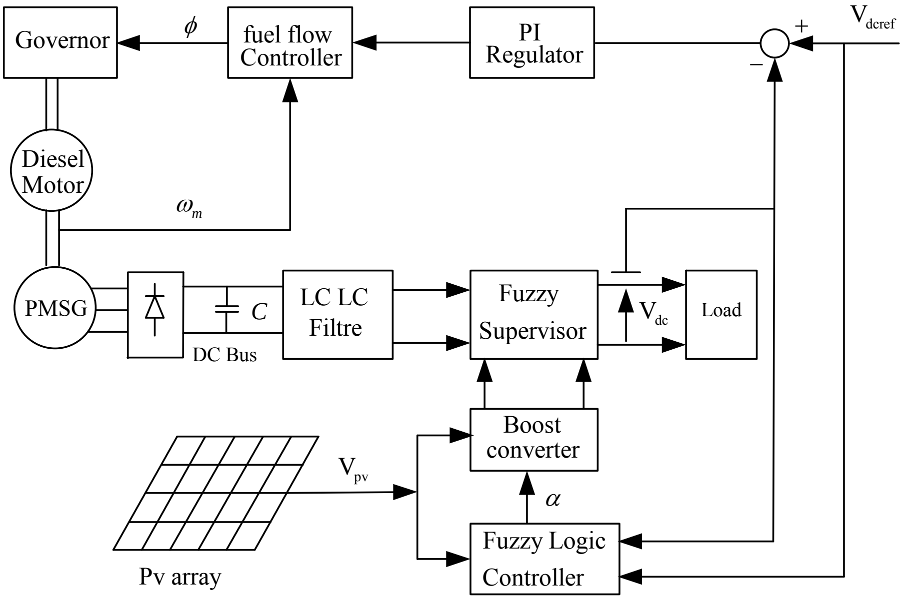

Fig. 1 The proposed hybrid system configuration

A. Cell and PV Models

Viewpoint principle, the solar cell allows the conversion of solar energy into electricity. In the photovoltaic literature, many models are proposed for the cell's description [5-10]. Fig.2 gives the schematic of the equivalent circuit of a solar cell's. It's composed of a the light-generated current source (I_{ph}), a diode (D), a series resistance (R_{sc}) and parallel resistance (R_{pc}), [6-8].

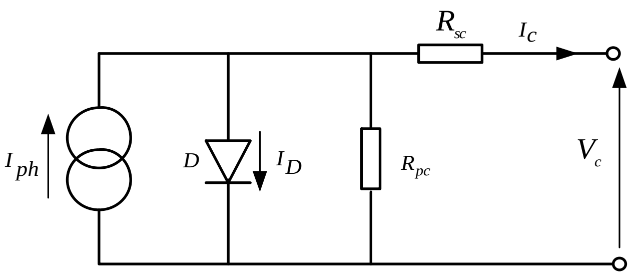

Fig. 2 Equivalent solar cell's electric circuit

Relation (1) gives the expression of the photocurrent cell I_{ph} where G , T_c and K_{SCT} are the insolation, the cell junction temperature and the short circuit current temperature coefficient.

$$I_{ph} = \frac{G}{G_{ref}}\left(I_{sc\_ref} + K_{SCT}\left(T_c - T_{c\_ref}\right)\right) \tag{1}$$

At the reference condition defined by the cell junction temperature T_{c_ref} and the insulation G_{ref} , the photocurrent I_{ph_ref} is equal to the reverse saturation current I_{sc_ref} .

Denote by E_g , q , k and β the band gap energy of the semiconductor, the electron charge, the ideal factor of the solar cell and the βoltzman constant respectively, the reverse saturation current I_{rs} can be expressed by:

$$I_{rs} = I_{rs\_ref}\left(\frac{T_c}{T_{c\_ref}}\right)^3 \exp\left[\frac{qE_g}{\beta k}\left(\frac{1}{T_c} - \frac{1}{T_{c\_ref}}\right)\right] \tag{2}$$

The expression of the cell's characteristic is given by (3) where I_c and V_c denotes respectively the current and the voltage cell.

$$I_c = I_{ph} - I_{rs}\left(\exp\left(\frac{q}{\beta k T_c}\left(V_c + R_{sc}I_c\right) - 1\right)\right) - \frac{\left(V_c + R_{sc}I_c\right)}{R_{pc}} \tag{3}$$

Consider a solar panel composed of N_p parallel groups of modules; each one is composed of N_s series modules. A module is composed of n_s series cells. This consideration expresses the relations between the panel's and the cells parameters, relation (4).

$$\begin{cases} I_p = N_p I_c \ ; \ V_p = n_s N_s V_c \\ R_{sp} = \dfrac{n_s N_s}{N_p} R_{sc} \ ; R_{pp} = \dfrac{n_s N_s}{N_p} R_{pc} \end{cases} \tag{4}$$

In this consideration, the non-linear characteristic equation related the panel current I_p to its voltage V_p is shown in (5), where $f_1\left(I_p, V_p\right)$ and $f_2\left(I_p, V_p\right)$ are given by (6).

$$I_p = N_p I_{ph} - f_1\left(I_p,V_p\right) - f_2\left(I_p,V_p\right) \quad (5)$$

$$\begin{cases} f_1\left(I_p,V_p\right) = N_p I_{rs}\left(\exp\frac{q}{\beta k T_c}\left(\frac{V_p}{n_s N_s} + \frac{R_{sc} I_P}{N_p}\right) - 1\right) \\ f_2\left(I_p,V_p\right) = \frac{N_p}{R_{pc}}\left(\frac{V_p}{n_s N_s} + \frac{R_{sc} I_P}{N_p}\right) \end{cases} \quad (6)$$

B. Boost Converter Model

Fig. 3 shows the schematic of the boost converter connected to the photovoltaic array and used in this research work.

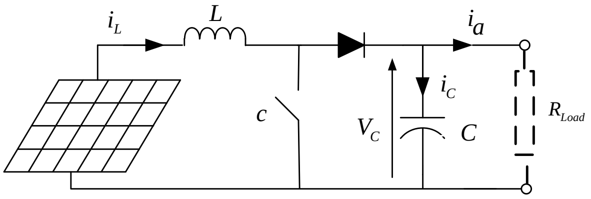

Fig. 3 Schematic of the boost converter

As a hypothesis, All the power devices used in this configuration are considered ideal and both inductive and capacitive loses are neglected.

The ideal switch state is controlled by a PWM signal characterized by the operating period (T) and the duty cycle (α) so that during the operating the time period (T), the switch is closed in αT and open in $(1-\alpha)T$.

If we designate by c a Boolean variable that takes the value $(c=0)$ if the ideal is switched off and the diode is switched on and takes the value $(c=1)$ if the ideal is switched on and the diode is switched off. According to this idea, the global model taking account of the boost converter model is given as:

$$\begin{bmatrix} \overset{\bullet}{i}_L \\ \overset{\bullet}{V}_C \end{bmatrix} = \begin{bmatrix} -\frac{R_L}{L} & -\frac{\bar{c}}{L} \\ \frac{\bar{c}}{C} & -\frac{1}{R_{Load} C} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{panel} \quad (7)$$

$$V_{dc} = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L & V_C \end{bmatrix}^t \quad (8)$$

C. PMSG model

Many authors proposed different models for permanent synchronous machines, [16], [17].

In the convention generator and relatively to the Concordia, applied to the machine winding, the ohm's low is given by relation (9):

$$\bar{v}_s = -R_s\, \bar{i}_s + \frac{d\bar{\varphi}_s}{dt} \quad (9)$$

The stator flux vector $\bar{\varphi}_s$ is linked to the rotor flux $\bar{\varphi}_r$ by relation (10) where θ_r represents the electric rotor position.

$$\begin{cases} \bar{\varphi}_s = -\bar{\varphi}_r - \frac{L_q}{2}\left(\bar{i}_s - \bar{i}_s^{*} e^{2j\theta_r}\right) - \frac{L_d}{2}\left(\bar{i}_s + \bar{i}_s^{*} e^{2j\theta_r}\right) \\ \bar{\varphi}_r = \Phi_r e^{j\theta_r} \end{cases} \quad (10)$$

Relation (11) express the electromagnetic PMSG torque where p is the pair pole number.

$$C_{em} = p\ \bar{\varphi}_s \wedge \bar{i}_s \quad (11)$$

When relation (11) is developed, the electromagnetic torque can be also expressed by:

$$C_{em} = p(\varphi_{sd}\, i_{sq} - \varphi_{sq}\, i_{sd}) \quad (12)$$

In the Park's synchronous frame, linked to the rotor, relation (9) becames (13), where ω_r means the electric rotor speed:

$$\bar{V}_s = -R_s\, \bar{I}_s + j\omega_r\, \bar{\Phi}_s + \frac{d\,\bar{\Phi}_s}{dt} \quad (13)$$

The direct and the quadratic components of the stator flux vector are given by relation (14):

$$\begin{cases} \Phi_{sd} = -\Phi_r - L_d I_{sd} \\ \Phi_{sq} = -L_q I_{sq} \end{cases} \quad (14)$$

D. Diesel engine model

The diesel engine developed torque (C_{de}) can be described by relation (15) where (ϕ) and (τ_{de}) are respectively the governor adjusted fuel flow and the introduce delay time combustion process, τ_{de}, [3],[11-13].

$$C_{de} = k_{de}.\phi(p) e^{-\tau_{de} p} \quad (15)$$

The governor is described by relation (16); it is an electromechanical device that receives a control signal S_{gs} in order to adjust the fuel flow [3],[11].

$$\phi(p) = \frac{k_g}{1+\tau_g p} S_{gc} \quad (16)$$

E. Diode rectifier model

The three phase full bridge rectifier is supplied by a three phase voltage of the PMSG given by:

$$\begin{cases} v_{s1} = v_{sM}\sin(\omega_0 t) \\ v_{s2} = v_{sM}\sin(\omega_0 t - \frac{2\pi}{3}) \\ v_{s3} = v_{sM}\sin(\omega_0 t - \frac{4\pi}{3}) \end{cases} \quad (17)$$

The output voltage of the full bridge rectifier can be expressed by (18):

$$v_{rec} = \max(v_{s1}, v_{s2}, v_{s3}) - \min(v_{s1}, v_{s2}, v_{s3}) \quad (18)$$

The operation laws of a full bridge three phase 6-diodes rectifier fed with a three phase voltage source:

$$V_{rec0} = \frac{3\sqrt{6}}{2\pi} v_{sM} = 1.654 v_{sM} \quad (19)$$

III. THE HYBRID SYSTEM CONTROL

The supervisory controller is used in order to select the adequate system operating mode when the demand power or the available renewable power varies. As shown on fig.4, three inputs are associated to the fuzzy controller; the error ε (relation (20)), the error derivative and the last state of the diesel generator. These inputs and the memorized last state of the diesel generator are used to generate the signal that defining the new state of the diesel generator. Table 1 and table 2 give the fuzzy rule tables defining the off state and the on state of the diesel generator respectively.

$$\varepsilon = P_{ref} - P_{dc} \quad (20)$$

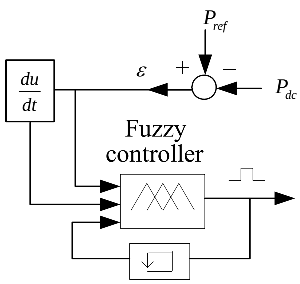

Fig. 4 Supervisory controller Structure

$d\varepsilon/dt$ \ ε	N	Z	P
N	P	Z	P
Z	P	Z	Z
P	P	Z	Z

Table 1. Fuzzy rule table of the supervisor: Last state of the diesel generator (off state)

$\frac{d\varepsilon}{dt}$ \ ε	N	Z	P
N	P	P	P
Z	P	P	Z
P	P	P	Z

Table 2. Fuzzy rule table of the supervisor: Last state of the diesel generator (on state)

IV. SIMULATION RESULTS

A. Power system transfer analyzes

The simulation in this work has been developed in Matlab/Simulink environnement.

Fig. 5 shows the proposed load profile, it covers a power range between 2 pu and 3 pu, where the nominal PMSG power equal to 1700 watt is considered as base value.

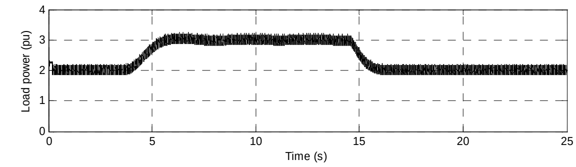

Fig. 5 Proposed load profile

Fig. 6 shows the panel power response at a considered insulation equal to 1000 W /m2. Fig. 7 gives PMSG power response which varies with the load in order to adapt the powers transfer between the generators and the load.

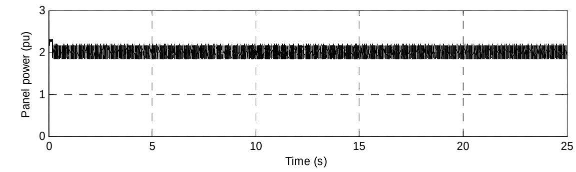

Fig. 6 Panel power response

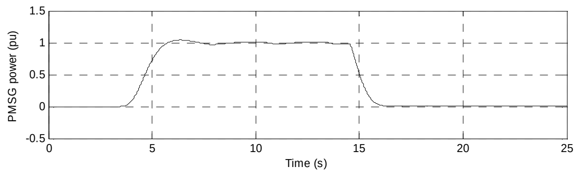

Fig. 7 PMSG power response

B. Analyzes physical sizes relating to the PMSG-diesel engine

The command of the PMSG-diesel system is based on the DC voltage required by the load equal to 490 V. This value is computed as a reference DC-bus voltage term.

Fig. 8 shows the voltage waveform $v_s(pu)$ of the PMSG stator phase. The generated voltage grows and reaches the rated value.

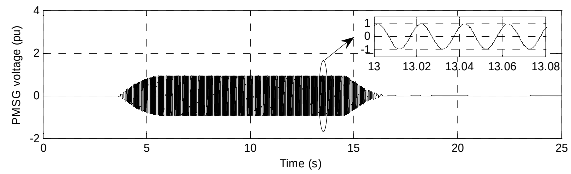

Fig. 8 PMSG voltage response

Fig. 9 gives the output rectifier voltage that result from a three sinusoidal signal rectified by full bridge 6 diodes rectifier.

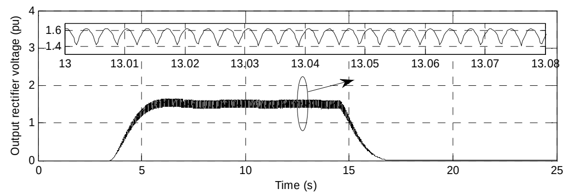

Fig. 9 Output rectifier voltage

Fig. 10 gives the evolution of the diesel engine speed that reaches the nominal value at the steady state.

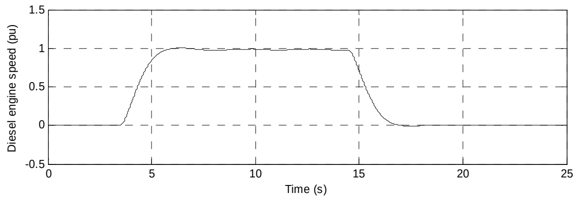

Fig. 10 Diesel engine speed

C. Analyzes physical sizes relating to the photovoltaic panel and the boost converter

The command of the boost converter is based on the DC voltage required by the load equal to 490 V. This value is computed as a reference boost voltage term. The figures 11 and 12 give respectively the panel's and the output boost converter voltages. The second one (fig. 12) converges towards the required DC voltage according to the first one.

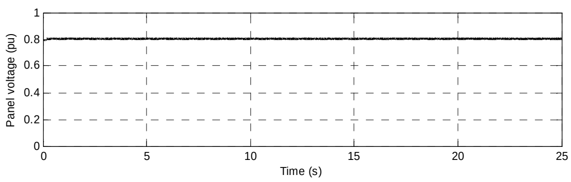

Fig. 11 The panel voltage

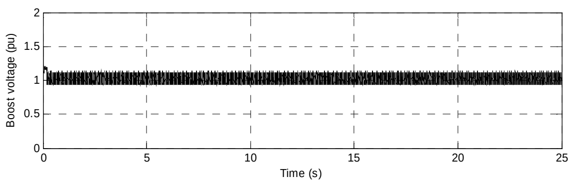

Fig. 12 Output boost converter voltage

V. CONCLUSION

The presented work leads to the development of dynamic controlled Photovoltaic PMSG-diesel topology and focusing on the system power management and the coordination of systems supervision. Diesel engine coupled to a permanent magnet synchronous generator (PMSG) has been found suitable for isolated area application. The uses of the boost converter and the conventional PI controller have respectively the advantages of the voltage adaptation and the speed regulation. The mutual exchange of information between the PV and diesel control output power bring up the system efficiency, a fuzzy supervisor is used in the context.

Appendix

TABLE I. PARAMETERS OF PV CELL (POLLY-CRYSTALLINE SILICON)

Open circuit voltage: V_{oc}	$0.6058\ V$
Short circuit current : I_{sc}	$8.1\ A$
Parallel cell's resistance: R_{pc}	$0.833\ \Omega$
Series cell's resistance: R_{sc}	$0.0833\ m\Omega$
Solar cell's ideal factor : k	1.450
reverse diode saturation current I_{rs}	$3.047e-7\ A$
Short circuit current temperature coefficient K_{SCT}	$1.73e-3A/°K$
Reference cell's temperature: T_{c_ref}	$25°C$
Boltzmann's constant: β	$1.38e-23$
Band gap energy: E_g	$1.11ev$

TABLE II. PARAMETERS OF PV MODULE

Rated output power	$216W$
Open circuit voltage: V_{oc}	$36.35\ V$
Number of series cells: n_s	60

TABLE III. PV ARRAY PARAMETERS

Open circuit voltage: V_{oc}	$545\ V$
Short circuit current : I_{sc}	$8.1\ A$
Number of series modules: N_s	14
Number of parallel modules: N_p	6

TABLE IV. PMSG PARAMETERS

Rated voltage V_s	220 V
Rated current I_N	3.3 A
Rated torque C_{emN}	8.1 N.m
Rated speed Ω_N	210 rad / s
Pole pairs p	4
Rotor flux Φ_r	0.61 Wb
Stator resistance R_s	2.015 Ω
d-axis inductance L_d	22.2 mH
d-axis inductance L_q	22.2 mH

TABLE V. TABLE 8. DIESEL ENGINE PARAMETERS

Actuator gain constant k_g	1
Actuator time constant τ_g (s)	0.125
Engine torque constant k_{de}	1.15
Engine delay time τ_{de} (s)	0.5
Plant and fly wheel acceleration $J(kg.m^2)$	0.3
Friction coefficient β (kg.m/s)	0.1

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