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A control strategy of hybrid photovoltaic-diesel generation system with battery storage for isolated load

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***Abstract*—A hybrid Diesel photovoltaic generator with energy conversion system is proposed with batteries in a DC-coupled structure. The objective of this system is to supply active power to an isolated load. This presented work focuses on the strategy, which makes it possible to ensure a high penetration of renewable energy and an overcharge security by designing a dedicated local control system. A continuous dynamic model and a control design of the power system studied are proposed in this paper. Simulation results illustrate the performances obtained**

Keywords— Diesel-engine, hybrid, supervisor, fuzzy controller, Photovoltaic, Battery.

I. INTRODUCTION

Hybrid systems combined renewable energy source that are never depleted, with other sources of energy [1]. Regardless of the intermittency of sunlight, solar energy is widely available and completely free of cost. Recently, photovoltaic array system is likely recognized and widely utilized to the forefront in electric power applications [2]. The performance of a PV module depends on the availability of solar irradiance and the PV-module temperature; It completely disappears during the night hours. There must be a standby 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 used to provide an uninterrupted energy sources in remote area, [3-4]. To improve the reliability and performance of these systems is to integrate energy storage devices into the power system network. The battery energy storage system comprises mainly of batteries, control and power conditioning system. A DC bus receives the power from the diesel engine coupled to the SEIG, PV panels interfaced through a DC/DC converter ,batteries energy storage system, transferred it to the load. The design process of hybrid energy systems requires the selection and sizing of the most suitable combination of energy sources. Thus in this paper a supervisor is developed and used to select the suitable energy source when the load varies [5-6]. To adjust voltage of the SEIG two control loops are included to stabilize the voltage frequency and magnitude. The first is the speed diesel engine control to maintain the speed constant, the second is called automatic voltage regulator which works to keep the voltage magnitude [7]. A fuzzy voltage controller is associated to the DC/DC converter in order to adapt the PV voltage and the DC bus voltage among the PV field, the energy storage unit and the Diesel engine [8]. The energy manager provides automatic dispatching energy, assigning priority to the exploitation of the renewable source.

II. THE CONTROLLED DIESEL-PV HYBRID SYSTEM

Related to works published in [7-9], the proposed diesel-PV hybrid system is shown in figure 1. It consists of PV arrays, diesel engine coupled to a SEIG, a three phase full bridge diode rectifier, LCLC, power conditioning system. , battery energy storage system. The power conditioning system is used to adapt the voltage produced to the load coupled to the DC bus, and an energy manager that provides automatic energy dispatching, assigning priority to the exploitation of the renewable source.

A. Diesel engine model

The developed torque C_{de} of the diesel engine can be expressed by relation**Error! Reference source not found.**, it depends of the fuel flow ø adjusted by the governor and the combustion process that introduce a delay time τ_{de} , [8-11].

$$C_{de} = k_{de}.\phi(p)e^{-\tau_{de}p} \qquad (1)$$

The governor modeled by relation **Error! Reference source not found.** is an electromechanical device that receives a control signal S_{gs} in order to adjust the fuel flow [8-10] .Where: k_g : Actuator gain constant, τ_g : Actuator time constant,

$$\phi(p) = \frac{k_g}{1+\tau_g p} S_{gc} \qquad (2)$$

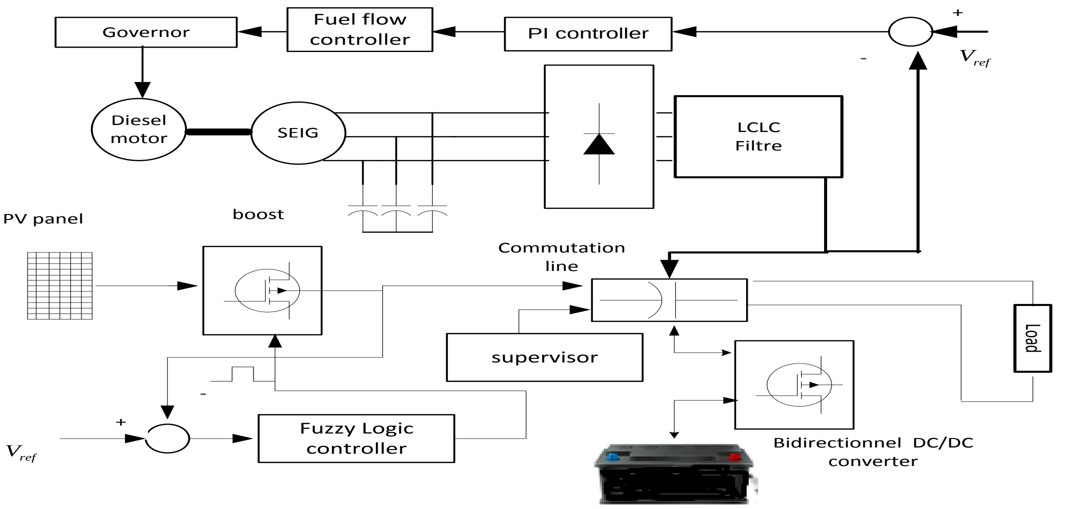

Fig1. The proposed Diesel-PV system

B. Self Exited Induction Generator Model

The voltage equations (3) in Concordia reference frame can be found from the equivalent circuit given by Figure 2.

$$\begin{bmatrix} \bar{V}_C \\ j\omega_r\bar{\phi}_r \end{bmatrix} = \begin{bmatrix} R_s + pL_s + pM_{sr} & pM_{sr} \\ pM_{sr} & R_r + pL_r + pM_{sr} \end{bmatrix} \begin{bmatrix} \bar{i}_s \\ \bar{i}_r \end{bmatrix} \quad (3)$$

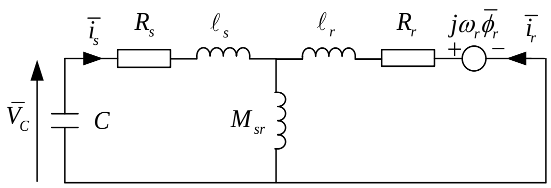

Fig2. Concordia reference frame SEIG

C. Diode rectifier model

The three phase full bridge rectifier is supplied by a three phase voltage of The SEIG given by (4):

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

The output voltage of the full bridge rectifier can be expressed by (5), [12]:

$$v_{rec} = \max(v_{s1}, v_{s2}, v_{s3}) - \min(v_{s1}, v_{s2}, v_{s3}) \quad (5)$$

D. LCLC Filter model

The LCLC filter used in this work is shown in figure: 3

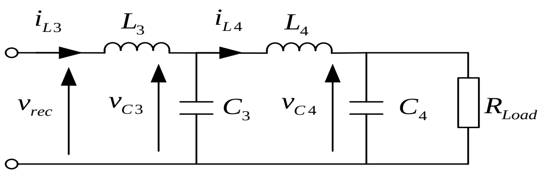

Fig3. LCLC filter structure

The state equation is (6):

$$\begin{bmatrix} \dot{i}_{L3} \\ \dot{i}_{L4} \\ \dot{v}_{C3} \\ \dot{v}_{C4} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_3} & 0 \\ 0 & 0 & \frac{1}{L_4} & -\frac{1}{L_4} \\ \frac{1}{C_3} & -\frac{1}{C_3} & 0 & 0 \\ 0 & \frac{1}{C_4} & 0 & -\frac{1}{R_{Load}C_4} \end{bmatrix} \begin{bmatrix} i_{L3} \\ i_{L4} \\ v_{C3} \\ v_{C4} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_3} \\ 0 \\ 0 \\ 0 \end{bmatrix} v_{rec} \quad (6)$$

E. Cell and PV Models

The electric model of a solar cell is shown in figure 4[6-7]-[13-14]. Where I_{ph}, D, R_{sc} and R_{pc} represent respectively the light-generated current source, the diode, the series and parallel resistances.

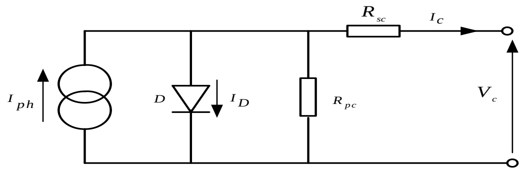

Fig4. Equivalent solar cell's electric circuit

The characteristic equation relating the cell's current I_c to its voltage V_c is represented in (7).

$$I_c = I_{ph} - I_{rs}\left(\exp(\frac{q}{\beta kT_c}(V_c + R_{sc}I_c) - 1\right) - \frac{(V_c + R_{sc}I_c)}{R_{pc}} \quad (7)$$

The solar panel can be composed of N_p array of modules assembled in parallel; each one can be composed of N_s modules assembled in series. A module can also contain n_s cells associated in series configuration. The relations between the panel's and the cells parameters, relation (8).

$$\begin{cases} I_p = N_p I_c \\ V_p = n_s N_s V_c \\ R_{sp} = \frac{n_s N_s}{N_p} R_{sc} \\ R_{pp} = \frac{n_s N_s}{N_p} R_{pc} \end{cases} \quad (8)$$

The equation related the panel current I_p to its voltage V_p is shown in (9)

$$I_p = N_p I_{ph} - N_p I_{rs}\left(\exp\frac{q}{\beta kT_c}\left(\frac{V_p}{n_s N_s} + \frac{R_{sc}I_P}{N_p}\right) - 1\right) - \frac{N_p}{R_{pc}}\left(\frac{V_p}{n_s N_s} + \frac{R_{sc}I_P}{N_p}\right) \quad (9)$$

F. Battery Model

The battery model used is essentially two RC Circuits connected in series, as shown in Figure5.

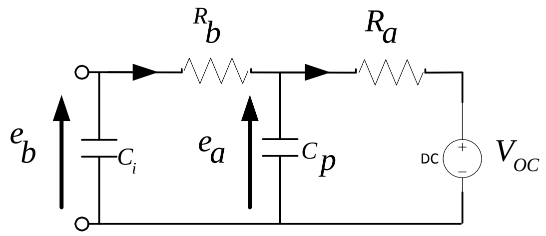

Fig.5RC model of the battery

The internal resistance R_a and the open circuit voltage v_{oc} are functions of the battery state of charge Q_{soc} . The voltages across the two capacitors and Q_{soc} are the three state variables for the battery [15](11,12,13):

$$v_{OC} = 338.8(0.94246 + 0.05754 Q_{SOC}) \quad (11)$$

$$R_a C_p \frac{de_a}{dt} + \frac{(R_a + R_b)e_a}{R_b} = V_{OC} + \frac{R_a e_b}{R_b} \quad (12)$$

$$R_b C_i \frac{de_b}{dt} + e_b = e_a - R_b i_{tb} \quad (13)$$

The battery state of charge Q_{SOC} Is the only state variable of the battery system, relation (14).

$$\frac{dQ_{SOC}}{dt} = \frac{I_{tb}}{Q_m} \quad (14)$$

I_{tb} is the battery current (A) calculated by relation (15).

$$I_{tb} = \frac{V_{OC} - \sqrt{V_{OC}^2 - 4(R_a + R_b)P_b}}{2(R_a + R_b)} \quad (15)$$

Where Pb is the output power (W) of the battery.

G. Boost Converter Model

This consists of basic RLC circuit a diode and switching element Figure 6. The aim of the circuit is to maintain a desired voltage upper than the photovoltaic panel voltage across the DC bus voltage.

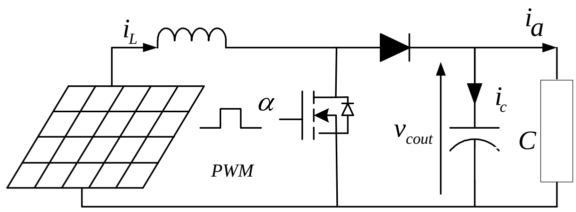

Fig6. Structure of the boost converter

We designate by i_a the current in the load, c a Boolean variable, the model of the boost converter is given as (16):

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} 0 & \frac{1-c}{L} \\ \frac{c-1}{C} & 0 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_{in} + \begin{bmatrix} 0 \\ -\frac{1}{C} \end{bmatrix} i_a \quad (16)$$

III. THE DIESEL_PHOTOVOLTAIC SYSTEM CONTROL

The electric generation hybrid systems are usually more reliable and less costly than the systems than use a single source of energy [19]. The mathematical design problem (sizing and control) involves a significant number of variables (load ,state of battery, diesel state, irradiation ,temperature) [19]. The hybrid system that will be used to explain the control strategy described in this paper is shown in Fig. 7.

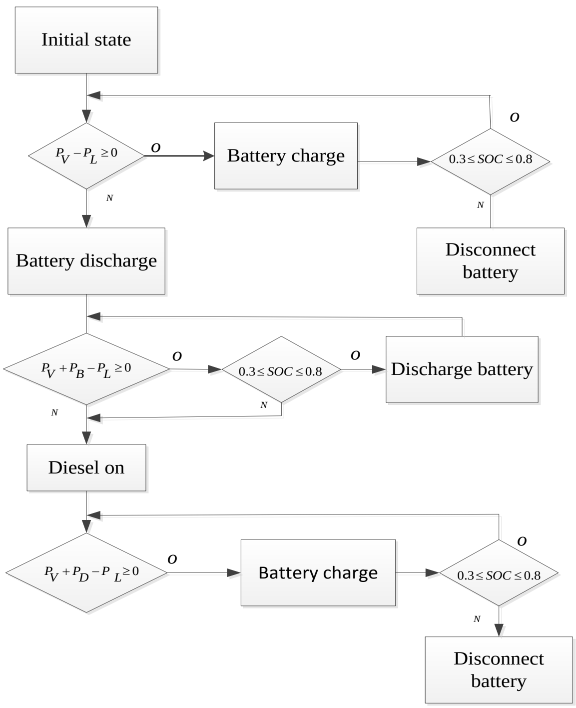

Fig7. Strategy of the control

A. *The Boost converter control*

A system with constant voltage control includes a DC–DC converter as shown in Figure 8. The converter duty ratio is adjusted using a fuzzy controller to keep the array voltage constant at the reference value. Duty cycle (α) indicated by relation (17).

$$V_{dc} = \frac{1}{1-\alpha} V_{panel} \qquad (17)$$

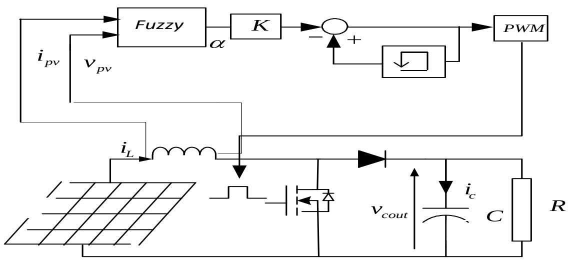

Fig8. Block diagram of the proposed fuzzy control Boost converter

A controller which does not depend directly on the converter's model has been proposed. These are known as "non-model based' controllers. Among the most popular of these is the Fuzzy Logic Controller (FLC), [16-18].

There are two inputs of fuzzy control. Input parameters error and its derivative respectively designed figure9 by $\left(\varepsilon = V_{ref} - V_{dc}\right)$, and $\left(\frac{d\varepsilon}{dt} = d\frac{\left(V_{ref} - V_{dc}\right)}{dt}\right)$ are used to generate the optimal converter duty cycle figure10, such that solar panel interfaced with boost converter gives the desired DC voltage.

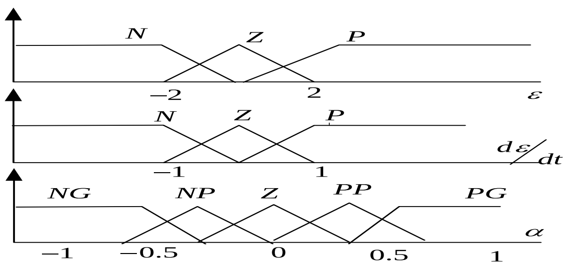

Fig9. The Structure of the controller

$d\varepsilon$ \ ε	N	Z	P
N	N	NP	Z
Z	Z	NP	PP
P	Z	PP	PG

Fig10. The Fuzzy rule table of the controller

B *The battery state of charge control*

The battery is associated to the system through a bi-directional DC/DC converter figure 11,

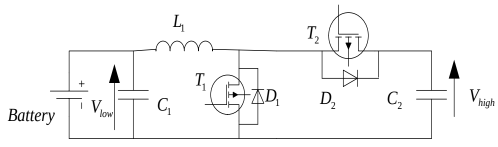

Fig11: Bi-directional DC/DC converter topology

The converter is used as a boost in charge, the elements considered are (L1, T1, D2) and as a buck in a discharge the elements considered are (L1, T2, D1), The key decision parameters is based on the accumulator the state of charge SOC and on the difference between the power produced and the power demand , $\Delta_p = P_V - P_L$. (SOC) is controlled through hysteresis controller that select the suitable switch to be active (T1 ,T2) to maintain the SOC upper than 0.3 lower than 0.8.

Diesel control

As mentioned above one part of operating a stand-alone power plant is to decide the power flow, in other words when to start the diesel engine, when to charge the battery etc. In an algorithm for deciding when to start or stop the diesel engine was proposed. The diesel engine is used when the $P_V + P_L$ is not enough and the SOC is under 0.3.

IV. SIMULATION RESULTS

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

A. Analyses of photovoltaic system

The insulation and current profile are given by figure 12 and figure13.

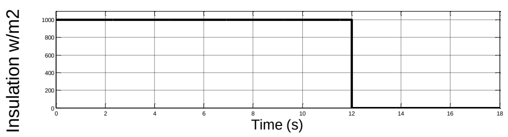

Fig12: Insulation profile

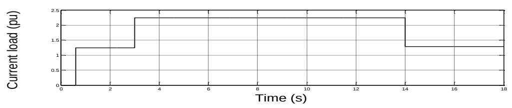

Figure 13 Load current profile

The command of the boost converter is based on the DC voltage required by the DC bus equal to 560V.The figures 14 and 15 give respectively the panels and the output boost converter voltages.

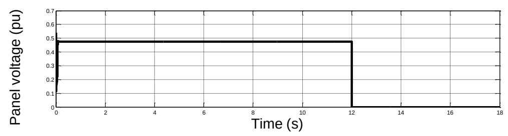

Fig14: Panel voltage

This nominal DC bus voltage is used as a reference for a feedback control loop that usually employs a fuzzy controller to adjust the duty ratio of a boost converter. Constant voltage control requires the measurement of panel voltage.

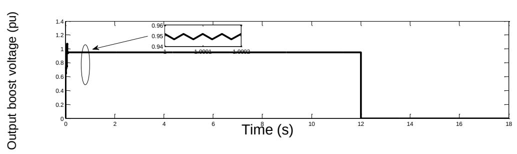

Figure 15 Output Boost converter voltage

Initially, the insulation is sufficient and the DC bus is supplied from the photovoltaic panel. when the insulation is insufficient (12 s) the output boost converter power is equal to zero. The figures 16 and 17 give respectively the panels and the output Boost converter current.

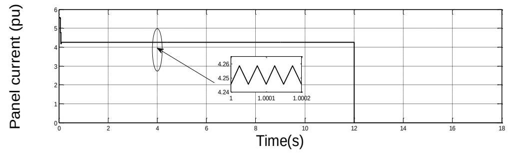

Figure 16: Panel current

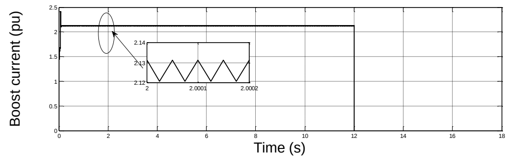

Fig 17. boost converter current

B. Analyzes of SOC Batterie .

The battery SOC figure (18) depend on the battery current figure (19) when the $\Delta_p = P_V - P_L \geq 0$ the current $I_{tb} \geq 0$ the battery is in the charge state and the SOC growth in the other case $\Delta_p = P_V - P_L \leq 0$ the current $I_{tb} \leq 0$ the battery is in the discharge state.

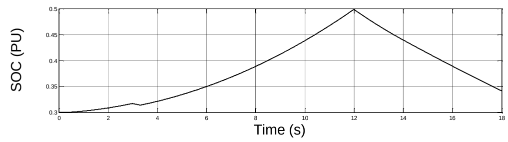

Fig18. Batterie SOC

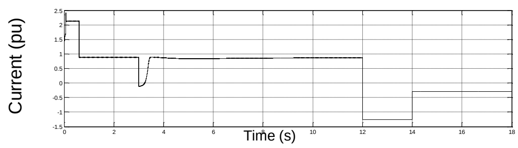

Figure 19. Battery Current

C. Analyses of diesel engine generator system

The command of the Diesel engine system is based on speed reference required by the load equal to 314 rad/s to maintain the DC bus voltage equal to 560v .This value is computed as reference speed term.When the SOC of the battery is lower than 0.3, the SEIG generator driven by the diesel engine is started it will be in off state when the SOC IS equal to 0.9 figure 20 and 21 gives respectively the current and diesel engine speed .

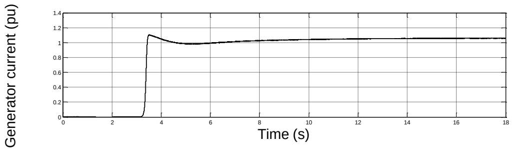

Fig20. Diesel engine Current

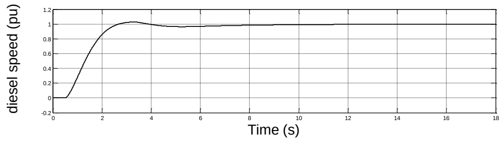

Fig21. Diesel engine Speed

V. CONCLUSION

This work presented leads to the development of an overall dynamic model for a controlled diesel photovoltaic system. Diesel engine has been found suitable for remote area application. A conventional PI controller is sufficiently enough for the shaft speed regulation. The steady-state and transient characteristics of PV panel with boost converter are obtained. From the simulation studies it is observed that the use of converter will have the influence both on the dynamic and steady-state behavior.

Appendix

TABLE – 1 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

TABLE – 2 Parameters of Pv module

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

TABLE – 3 PV Array Parameters

Open circuit voltage: V_{oc}	109 V
Short circuit current : I_{sc}	$8.1A$
Number of series modules: N_s	8
Number of parallel modules: N_p	10

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