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MPPT Control of Wind Turbine for Water Pumping System

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***Abstract* –A control scheme of water pumping system based on wind turbine generator in an isolated area is presented. The wind energy conversion system (WECS) is used to drive the Permanent Magnet Synchronous Generator (PMSG) in order to feed the isolated load which is composed of DC motor drives a hydraulic centrifuge pump. In order to maximize the extracted energy of wind energy, we applied the strategies of maximum power point tracking (MPPT) with optimal torque control which allows the PMSG to operate at an optimal speed. The models of the wind turbine, the PMSG, DC motor and the control scheme are developed and analyzed. Simulation results have proven good performances and verified the validity of the proposed pumping system.**

Keywords – Wind energy conversion system (WECS) , maximum power point tracking (MPPT) control, Water pumping system, Permanent Magnet Synchronous Generator (PMSG).

NOMENCLATURE

t: time [s]
P_m: The power captured by the wind turbine [W]
P_H :hydraulic power [W]
A: blade swept area [m^2]
ρ: specific density of air [kg/m^3]
R_t : radius of the turbine blade [m]
V_1 : wind speed [m/s]
Ω_t: mechanical turbine speed [rpm]
Ω_g: mechanical generator speed [rpm]
Ω_m: mechanical motor speed [rpm]
Ω_{ref} : reference mechanical speed [rpm]
λ: tip-speed ratio (specified speed)
C_p : power coefficient
β: pitch angle [°]
P_{opt}: optimal power captured by the wind turbine [W]
λ_{opt}: optimal tip-speed ratio
b_0, b_1 and τ : controller parameters
S :Laplace magnitude.
T_{em} : electromagnetic generaotor torque [N.m]
T_{em_ref} : reference generator torque [N.m]
T_M : motor torque [N.m]
C_{ass}: speed controller.
v_{ds} ,v_{qs} :d-q axis stator voltage [V]
i_{ds} ,i_{qs} : d-q axis stator current [A]
L_d L_q: d-q axis inductance [mH]
R_s : stator resistance [Ω]
ω : electric pulsation [rad/s]
φ_f: generator rotor flux [Wb]
p: number of poles pairs.
K: torque constant [N.m/A]
v_g,i_g: respectively are grid voltage and grid current.
d,q: respectively are direct and quadrature components,
V_{dc}:DC-link voltage

I. INTRODUCTION

Nowadays, the research on WECS knows a big growth, mainly due to the environment pollution and the oil crisis. The research development, the interest in wind energy applications and power electronics allow manufacturers to find the most suitable solutions and low cost technologies. The most used generator in WECS are double fed induction generator and PMSG. Actually, the PMSG has become a more attractive solution to use it in variable speed wind turbine applications. In our study, we chose PMSG due to its advantages such as the high efficiency and reliability, small size and easy to control, more than that, there is no need of external excitation which decreases Joule losses [1], [2].

In Algeria, the wind resources vary greatly from location to another due to a very diverse topography and climate. The region of Adrar located in South Algeria is among the windiest areas, it presents an excellent potential of wind energy. At first, the wind energy was only used for pumping water using mechanical system; the first experience of pumping water by wind turbine in Africa was conducted in 1957 "*Ksar Ouled Aroussa*" (in Adrar) for irrigation of 50 hectares [3]. In Adrar, The annual mean of the wind speed reaches over than 6m/s [4]. Which allows the use of wind turbine in supplying electrical energy to remote areas (Forages, Kessour, …etc), where the connection to the grid is not possible or very expensive [3]. For this reason, the 1st national wind turbine project was born in Kaberten(72km north the Willaya of Adrar), this new power generation central has a capacity of 10 megawatts, with a surface of 30 hectares, it is constituted by 12 wind turbines connected to grid with an output of 0.85MW each, as it is shown in the figure below:

Fig.1. Wind turbines in the zone of Kabertene, Adrar

In our study, the water pumping system used a wind turbine based on PMSG which supplies DC motor to generate the torque required to the centrifuge hydraulic pump[5], [6], "Fig.2''.

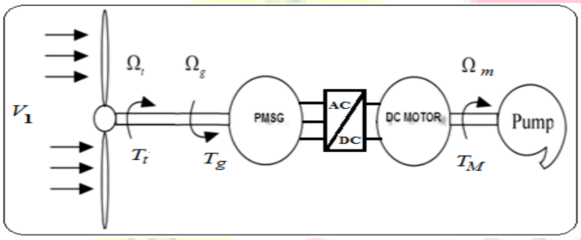

Fig.2. Wind turbine pumping system

II. Modelling and Control of the Wind Turbine

The wind turbine collects the kinetic energy of the wind and converts it into mechanical energy which drives the blades of the rotor [6]. The evolution of the used power coefficient is given by the following relation [7]:

$$C_p(\lambda,\beta)=(0.5-0.0167(\beta-2))\sin\left[\frac{\pi(\lambda+0.1)}{18-0.3(\beta-2)}\right]-0.00184(\lambda-3)(\beta-2) \quad (1)$$

The simulation of "(1)" is shown in "Fig.3"

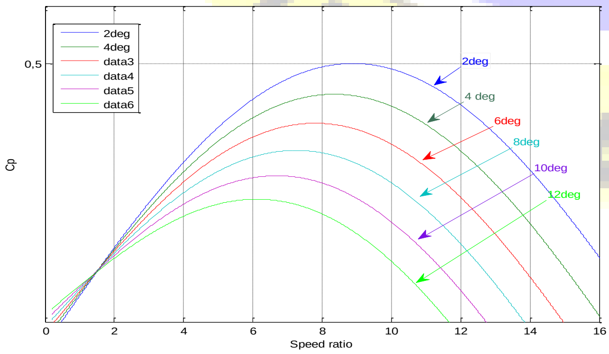

Fig.3. *C p (λ,β)* Characteristics for various values of *β*.

The power captured by the wind turbine may be written as [8]:

$$P_m = \frac{1}{2} C_p(\lambda)\rho A V_1^3 \quad (2)$$

The tip-speed ratio is defined as [8]:

$$\lambda = \frac{\Omega_t R_t}{V_1} \quad (3)$$

Where,

A: blade swept area [m^2]
ρ: specific density of air [kg/m^3]
V_1 : wind speed [m/s]
R_t : radius of the turbine blade[m]
Ω_t: rotating speed [rpm]
C_p : coefficient of power conversion

The mechanical torque of the wind turbine system can be described by the following equation:

$$T_t = \frac{P_m}{\Omega_t} = \frac{1}{2}\rho\pi R^3 \frac{C_p(\beta,\lambda)}{\lambda} V^2 \quad (4)$$

In MPPT zone where the wind power is less than nominal value, we fix the value of pitch angle constant ($\beta = 2$), so value of C_p becomes a function of λ and it reaches the maximum (C_p^{opt} =0.5) at the particular λ named λ_{opt}.
Hence, to maximize the wind energy, λ should be maintained at (λ_{opt} =8.7) "Fig.4".

Fig.4. Characteristics of power coefficient

In order to maintain the power coefficient at its maximum we use the MPPT control.

A. MPPT Control

The goal of the (MPPT) strategy is to pick up the maximum power from the wind; it involves the following of the power curve shown in "Fig.5", given by in equation (5):

$$P_{opt} = \frac{1}{2} C_p^{opt}(\lambda_{opt})\rho A V_1^3 \quad (5)$$

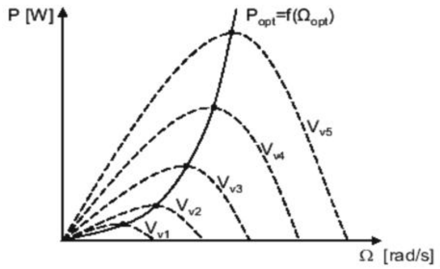

Fig.5 MPPT and power characteristics in function of mechanical speed

A.1 MPPT With optimal torque Control

The speed controller regulates the speed of the rotor by controlling the generator electrical power (and therefore the torque) according to the optimal specified speed λ_{opt}, by imposing on the generator torque to equal to its reference value [9]:

$$T_{em} = T_{em-ref} \qquad (6)$$

The reference electromagnetic torque T_{em_ref} allows obtaining a mechanical speed of the generator equals to the reference speed Ω_{ref} by the relation below, [9]:

$$T_{em-ref} = C_{ass}\left(\Omega_{ref} - \Omega_{mec}\right) \qquad (7)$$

Where:
C_{ass}: speed controller.

The reference speed of the turbine corresponds to the optimal value of specific speed λ_{opt} and the maximum of power coefficient C_p^{opt} is given by:

$$\Omega_{tur-ref} = \frac{\lambda_{opt} . V_1}{R_t} \qquad (8)$$

By developing the proportional integral PI controller, the reference torque becomes, [9],[10]:

$$T_{em-ref} = \left(\frac{b_0 + b_1 . S}{S}\right).\left(\Omega_{ref} - \Omega_{mec}\right) \qquad (9)$$

b_0, b_1 and τ are controller parameters to determinate, S is Laplace magnitude.

The dynamic equation of turbine with generator can be given by:

$$T_t - T_{em} = J\frac{d\Omega_g}{dt} + f\,\Omega_g \qquad (10)$$

Where,
T_t , T_{em}: respectively turbine and generator torque [N.m]
J: inertia on generator rotor with turbine [kg.m^2]
f: friction of generator with turbine[N.m/rad/s]

We deduce the following diagram, "Fig.6"

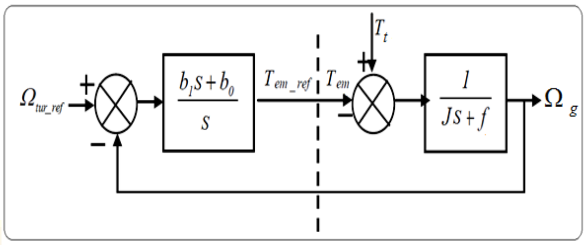

Fig.6 Diagram block of the PI controller

Figures "8", "9", "10" and "11" show the simulation results of MPPT strategies by using the wind profile of "Fig.7".

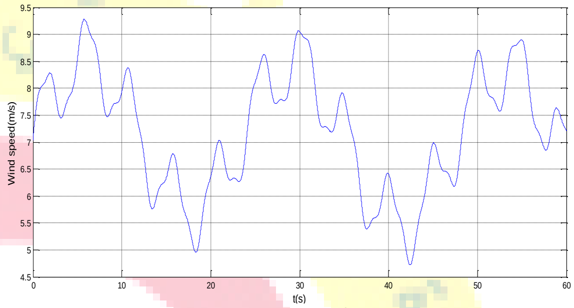

Fig.7 Wind profile

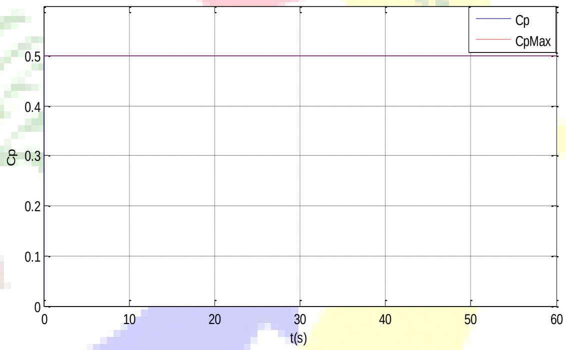

Fig.8 Coefficient of power conversion

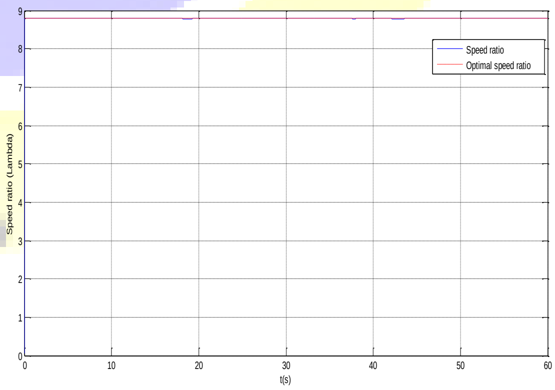

Fig.9 Speed ratio

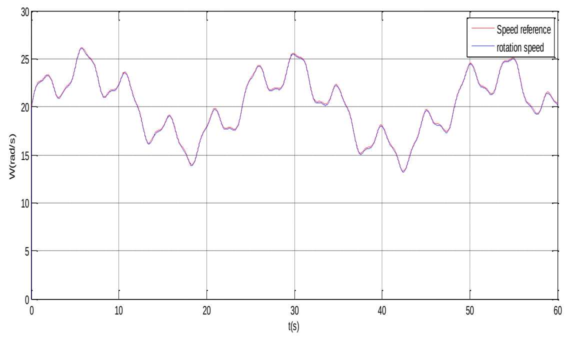

Fig.10 Mechanical speed

A.2.Results analysis

It is seen that the wind speed is variable; however, power coefficient remains constant. We observe that the power coefficient and the speed ratio follow very well their references corresponding to maximum and optimal speed “Fig. 10”, which involves extracting of the maximum power.

III. MODELLING OF WIND TURBINE PUMPING SYSTEM

A. PMSG model

The voltage equation of the PMSG is expressed at synchronous reference frame by, [8], [11]:

$$\begin{cases} v_{ds} = -R_s i_{sd} - L_d \dfrac{di_{sd}}{dt} + \omega L_q i_{sq} \\ v_{qs} = -R_s i_{sq} - L_q \dfrac{di_{sq}}{dt} + \omega L_d i_{sd} + \omega.\Phi_f \end{cases} \quad (11)$$

Where:
v_{ds}, v_{qs} :*d-q* axis stator voltage
i_{ds}, i_{qs} : *d-q* axis stator current
L_d L_q : *d-q* axis inductance
R_s : stator resistance
ω : electric pulsation
Φ_f: magnetic flux of permanent magnet

The electromagnetic torque is expressed as, [8]:

$$T_{em} = \frac{3}{2} p\left[\left(L_q - L_d\right) i_{ds} i_{qs} + i_{qs}\varphi_f\right] \quad (12)$$

Where

p: number of poles pairs.

By using the vector control, q-axis is aligned with the magnetic flux, then, [8]:

$$T_{em} = \frac{3}{2} p.i_{qs}\varphi_f = K.i_{qs} \quad (13)$$

The q-axis current component can be used for the speed control of the generator, and d-axis current is set to zero [12], [13].

B. DC Motor model

In this work, DC machine is operated in motor mode. Ohm’s law describing the armature winding and the field winding are respectively given by the relations below, [6]:

$$\begin{cases} V_{ma} = K.w + R.i_a + \dfrac{Ld\, i_a}{dt} \\ V_{mf} = R\ .i_f + \dfrac{Ld\, i_f}{dt} \end{cases} \quad (14)$$

The electromagnetic motor torque is given by, [11]:

$$T_M = K i_a \quad (15)$$

C. Model Of PWM Rectifier

Contrary to the traditional rectifiers, PWM rectifiers are controlled by opening and closingsemiconductors in a way allows obtaining the imposed DC voltage references according to needs. Thus, we have a total control of the converter [13], [14]. This rectifier is controlled to keep the voltage of the continuous bus at a wished value of reference, by using a closed loop control, as it is shown in “Fig.11”.

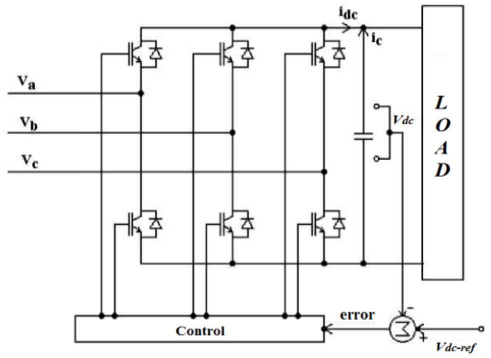

Fig.11. Basic topologies of a rectifier of voltage

We can simplify modelling and reduce the time of simulation by modelling the rectifier with ideal switches, these switches being complementary; their state is defined by the following function, [15]:

$$S_j = \begin{cases} +1, S_j = -1 \\ -1, S_j = +1 \end{cases} \quad (16)$$

The simple input voltages and the output current can be written in function of S_j, V_{dc} and the input currents i_{sa}, i_{sb}, i_{sc}.

$$i_{sa} + i_{sb} + i_{sc} = 0 \quad (17)$$

The compound input voltages of the rectifier can be described by

$$\begin{aligned} U_{Sab} &= (S_a - S_b)*V_{dc} \\ U_{Sbc} &= (S_b - S_c)*V_{dc} \\ U_{Sca} &= (S_c - S_a)*V_{dc} \end{aligned} \quad (18)$$

Voltage equations of the three-phase system balanced without connection to neutral point can be written as follows:

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = R_s \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + L_s \frac{d}{dt} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} \quad (19)$$

With:

$$U_{sa} = \frac{2S_a - S_b - S_c}{3} V_{dc}$$
$$U_{sb} = \frac{2S_b - S_a - S_c}{3} V_{dc} \quad (20)$$
$$U_{sc} = \frac{2S_c - S_a - S_b}{3} V_{dc}$$

Finally, we deduce the equation from coupling the AC and DC sides:

$$C.\frac{dV_{dc}}{dt} = (S_a.i_a + S_b.i_b + S_c.i_c) - I_L \quad (21)$$

D. Modelling of Hydraulic pump

The centrifugal pump model can be described by Knowing the mechanical characteristics '*h*' illustrated in relation (22), [6], [16]:

$$h = a_0\Omega_m^2 - a_1\Omega_m Q - a_2 Q^2 \quad (22)$$

Where: a_0, a_1, a_2 and Q are manufacture pump coefficients.

The hydraulic power P_H and the torque of the centrifugal pump can be given respectively by (24) and (25), [6] [16] :

$$P_H = \rho g H \quad (24)$$
$$T_{rp} = \alpha.\Omega_m^2 + T_s \quad (25)$$

Where: α, T_s are constants depend on hydraulic part.

The mechanical dynamic model of the electric motor and the centrifugal pump can be described by relation (26)

$$T_M = J_{mp}.\frac{d\Omega_m}{dt} + f_{mp}.\Omega_m + T_{rp} \quad (26)$$

Where:

T_M and T_{rp} represent respectively the motor torque and the hydraulic load torque of the pump.

J: inertia on motor rotor with pump [kg.m^2]

f: friction of motor with pump[N.m/rad/s]

IV. Simulation Results and Discussion

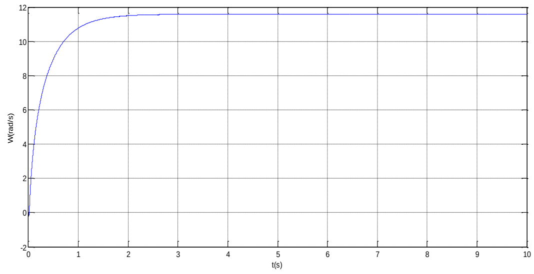

Fig.12 Rotor speed of generator PMSG

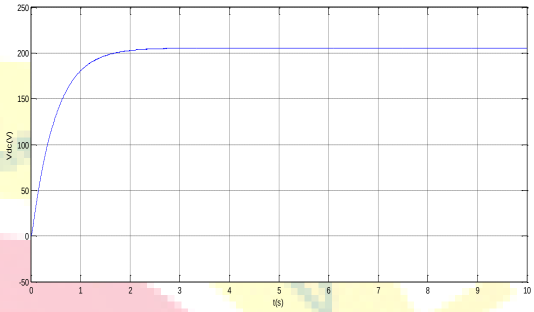

Fig.13 DC bus voltage

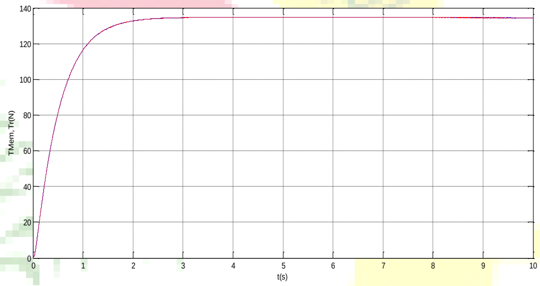

Fig.14 Electromagnetic motor torque & load torque

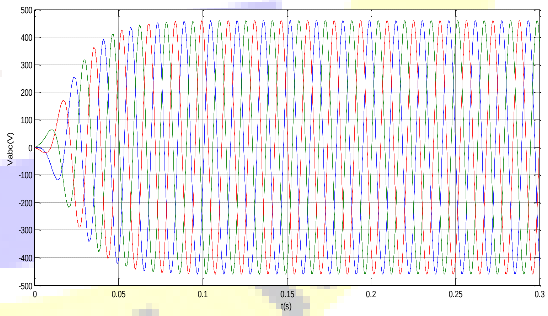

Fig.15 Stator voltage of PMSG

- *Analysis of Simulation Results*

Firstly, the rotor speed of PMSG increases converge towards its target intil reaching the steady state "Fig.12", as well as DC voltage "Fig.13", consequently the electromagnetic torque of motor increases and equals to the pump load "Fig.14"

We see that the stator tensions are sinusoidal that improve the performances of PMSG "Fig.15".

Spite of increasing or decrease in wind speed, the speed of the continuous voltage is established with a response time which depends on the control of the rectifier.

V. CONCLUSION

In this work MPPT control for wind turbine water pumping system based on DC machine is developed and simulated. We tried to enhance the efficiency of the system by choosing PMSG which has better efficiency compared to induction machine, then we applied MPPT to maximize the picked up power from the wind. When the power control scheme is applied to proposed wind turbine pumping system, both generator and turbine torques are adapted to the load power when the wind varies. Simulation results have shown good performances of the proposed control system. These promising results open the possibility for the reconstitution of the proposed scheme to be set up for an on-line implementation.

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