Modeling and Simulation of a Wind-diesel Hybrid Power System for Isolated Areas

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ABSTRACT
In many isolated areas situated in south Algerian, the diesel generators are the major source of electric energy. Indeed, the alimentation power of these remote areas still poses order problems (technical, economical and ecological). The electricity produced with the help of diesel generators is relatively inefficient, very expensive and responsible for the emission of greenhouse gas. These isolated areas have significant wind energy potential; which puts him in good position for the exploitation of clean and sustainable wind energy. The use of Twinning Wind-Diesel (TWD) is widely recommended especially to reduce operating deficits. However, the profitability of TWD is attained the condition to obtain a high penetration ratio of wind energy: which is possible only when using energy system storage. For hybrid energy storage systems plays a vital role, different storage technologies, we chosen for our study the battery energy storage system (BESS) still represent the most cost-effective technology. The subject of this paper is to present the modeling of a Wind Diesel Hybrid System (WDHS) comprising a Diesel Generator (DG), a Wind Turbine Generator (WTG), the consumer load, a Ni–MH Battery and a Distributed Control System (DCS).

Keywords
Wind turbine, diesel generator, autonomous grid, storage system, management, modeling.

1. INTRODUCTION
Energy is one of the major inputs for the economic development of any country. In the case of the developing countries, the energy sector assumes a critical importance in view of the ever increasing energy needs requiring huge investments to meet them. The growth of the world's human population has created several problems. One of them is global warming caused by the abundance of CO_2 in the atmosphere. Many of these gases are produced from electrical plants burning fossil fuel all over the world [1].

The electrical energy demand is increasing constantly and this demand has to be met by a planned electrical power generation programmer. Although electrical energy is environmentally the most benign form of energy, its production is routed through burning of conventional fossil fuel or nuclear energy or hydro resources. All of these, in addition to other disadvantages, give rise to environmental issues of varied nature. To minimize the environmental degradations, one of the solutions is to utilize wind energy in favorable remote sites, away from the centralized energy supply systems [2].

Nevertheless, in isolated areas, electrical energy is often produced with the help of diesel generators such as the Algerian Sahara (Adrar, Bechar, In Salah, Timimoun, Tindouf, Amenas, etc). But numerous isolated areas have significant wind energy potential. It is then interesting to associate with a diesel some wind generators as diesel electricity is generally more expensive than wind electricity. To reduce fuel consumption and power variations of the diesel, an energy storage system can be associated with the wind–diesel system [3]. A hybrid wind-diesel power generation systems have a great potential in the application of providing energy supply for remote communities and facilities. Compared to the traditional diesel system, hybrid power plants can offer many advantages such as additional capacity, being more environmentally friendly, potential reduction of cost, etc. [4].The subject of this paper is to present the modeling and simulation of an isolated Wind Diesel Hybrid System (WDHS) comprising a Diesel Generator (DG), a Wind Turbine Generator (WTG), the consumer load, a Ni–MH battery based Energy Storage System (BESS). The model modeling of hybrid system is based on control strategy to optimize the power output, regulate voltage and frequency transmitted to consumers.

2. WIND ENERGY RESOURCE IN ALGERIA
All The wind energy resource in Algeria varies greatly from one place to another. This is mainly due to a very diverse topography and climate. Algeria is a moderate wind regime (2 to 6.5 m/s). The map shown in Figure 1 shows that the South is characterized by higher speeds than the North, especially in the South-West, with greater speeds than 4 m/s, that exceed the value of 6 m/s at Adrar region. On the North, we note that the overall average speed is low [5].

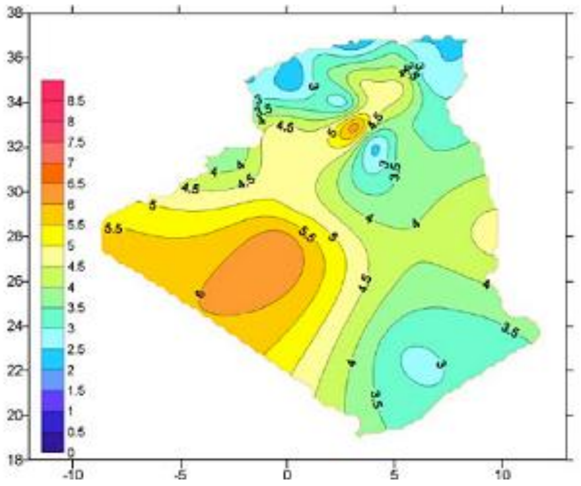

Fig 1: Annual maps of wind speed in Algeria at 10 m high

The climate data of wind speed recorded at Adrar region (Algeria) for the year 2012 were measured at the weather station of the Renewable Energy Research Unit in Saharian Medium (URER-MS) Adrar.(see Table 1 below), [6].

Table 1. Climate data for a studied site

Months	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
***v* (m/s)**	6,44	6,22	6,05	5,33	6,27	5,27	7,78	6,41	4,94	4,8	4,86	5,58

3. WIND-DIESEL HYBRID SYSTEM (WDHS)

3.1 Description of a WDHS

The underlying hybrid wind-diesel system is illustrated in Figure 2. The hybrid generation system is composed of a wind turbine generator (WTG), diesel generator (DG), battery bank, consumer load, power electronic converters (AC/DC rectifier, DC/AC inverter), monitoring system, distributed control system, switches and relays, controller and other accessory devices and cables [7-8].

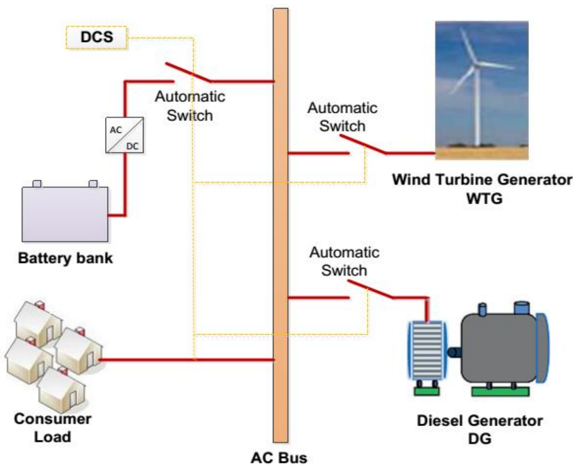

Fig 2: Schematic diagram of the hybrid wind-diesel generation power system

3.2 Operating regimes of a WDHS

Depending on the strength of the wind, there are three modes for systems with high penetration, (see Figure 3) [8]:

1. Weak winds ($v_w \leq 3$ m / s): diesel only.
2. Moderate winds (3m / s < $v_w \leq 10$ m / s) wind turbines and diesels in service.
3. Strong winds ($v_w > 10$ m / s) wind only.

Where: v_w is the wind speed upstream of the turbine.

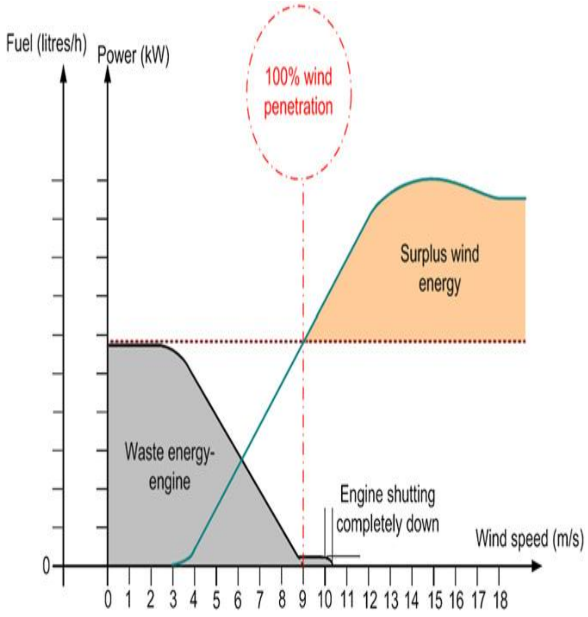

Fig 3: Variation of energy covered by a WDHS and diesel consumption as a function of wind speed

4. SIMULATION MODELING OF HYBRID SYSTEM COMPONENTS

4.1 Modeling of wind turbine system

4.1.1 Wind model

The wind speed can be modeled by a sum of some harmonious [9]:

$$V_v(t) = B + \frac{2}{\pi} \sum A_i . \cos(\omega_i . t + \varphi_i) \qquad (1)$$

Where: $\boldsymbol{B}$ is the constant and $\boldsymbol{A_i}$ is the amplitudes of harmonious, $\boldsymbol{\omega_i}$, $\boldsymbol{\varphi_i}$ represent respectively, the pulsations and phases.

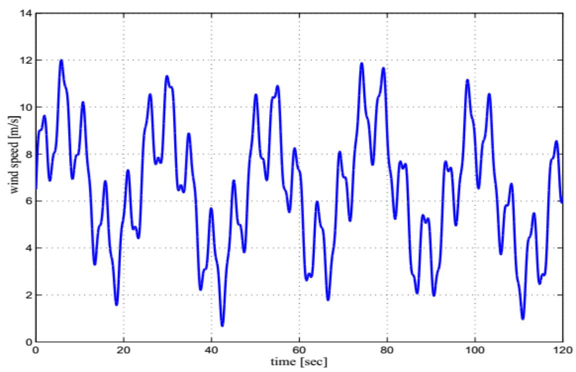

Fig 4: The wind speed profile

4.1.2 Wind turbine model

A wind turbine can only convert a certain percentage of the captured wind power. This percentage is represented by $\boldsymbol{C_P}$ which is a function of the wind speed, the turbine speed and the pitch angle of any specific wind turbine blades [10-11].

The mechanical power $\mathbf{P_{mec}}$ extracted from the wind is mainly governed by three quantities namely: the area swept by turbine blades **S**, the wind speed $\boldsymbol{v_w}$ and the rotor power coefficient $\boldsymbol{C_p}$ by following equation [12]:

$$P_{mec} = \frac{1}{2}\rho \cdot S \cdot v_{\omega}^{3} \cdot C_p(\lambda, \beta) \qquad (2)$$

Where ρ is the air density [kg/m^3]

In this paper, $\mathbf{C_P}$ is the power coefficient of rotor has been defined by Eq. (3), [12]. Power coefficient is a function of tip speed ratio (TSR) **λ** defined by Eq. (4) and pitch angel **β**. The wind turbine considered in this work is stall controlled, so pitch angel is kept constant, is considered zero where the $\boldsymbol{C_P}$ value would be 0.48 and $\boldsymbol{C_P}$ is a function of **λ** (λ = 8.1), [10-11].

$$C_p = 0.22(116.\lambda_i - 0.4\beta - 5)e^{-12.5\lambda_i} \qquad (3)$$

$$\lambda = \frac{\omega_r \cdot R}{v_{\omega}} \qquad (4)$$

Where $\mathbf{\Omega_r}$ is the rotor rotational speed and **R** is the wind turbine rotor radius.

Thus the maximum power captured from the wind is given by [13]:

$$P_{mec}^{\max} = \frac{1}{2}\rho \cdot S \cdot v_{\omega}^{3} \cdot C_p^{\max}(\lambda_{opt}, \beta) \qquad (5)$$

4.1.3 PMSG model

The model of permanent magnet synchronous generators (PMSG) is composed of two electrical differential equations and one mechanical differential equation. The electrical equations, expressed in direct (d) quadrature (q) coordinate are given by [14]:

$$\begin{cases} U_d = -R_s \cdot i_d - L_d \dfrac{d_{id}}{dt} - \omega_r \cdot L_q \cdot i_q \\ U_q = -R_s \cdot i_q - L_q \dfrac{d_{iq}}{dt} + \omega_r \cdot L_d \cdot i_d + \omega_r \cdot \varphi_f \\ T_e - T_{mec} - \Omega_r \cdot F = J_r \cdot \dfrac{d\Omega_r}{dt} \end{cases} \qquad (6)$$

Where $\boldsymbol{U}$ denotes voltage, $\boldsymbol{i}$ denotes current, $\boldsymbol{\varphi}$ represents magnetic flux, $\boldsymbol{R_s}$ denotes resistance and $\boldsymbol{L}$ inductance, indexes $\boldsymbol{d}$ and $\boldsymbol{q}$ stand for the direct and quadrature components, $\mathbf{\omega_r}$ is the generator electrical speed $(\mathbf{\omega_r = p.\ \Omega_r})$ and $\boldsymbol{\varphi_f}$ is the magnetic flux of the permanent magnets.

$\mathbf{T_{mec}}$ is the mechanical torque from the generator shaft, $\mathbf{T_e}$ is the generator electromechanical torque, $\mathbf{J_r}$ is the aerodynamic rotor inertia, $\mathbf{\Omega_r}$ is the generator angular velocity, **F** is the viscous friction coefficient from the generator shaft and **p** is the number of pair poles.

4.2 Modeling of diesel generator

The DG is generally constituted by a diesel engine and synchronous generator SG. The complete dynamic model of DG requires modeling diesel engine with speed control, a SG with the system voltage control and clutch between the SG and diesel engine (Figure 5), [15-16].

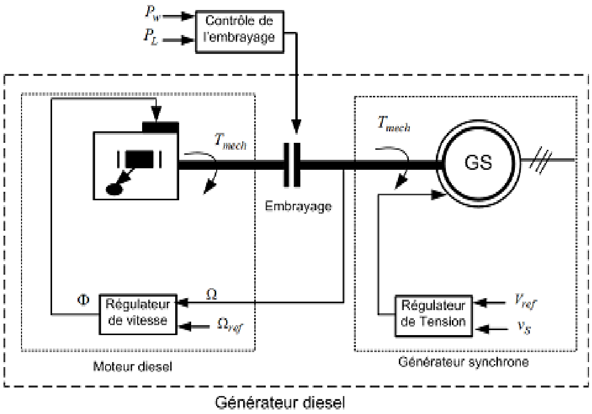

Fig 5: Model simplifies the diesel generator

4.2.1 Diesel engine model

The block diagram of the diesel engine is shown in Figure 6. The input signal is the speed (frequency) error and the output is the control signal of the actuator. The dynamics operation of the actuator is approximated by a transfer function with the gain K, which adjusts the relation between the torque and the fuel consumption [17]:

$$G(s) = \frac{K.(1+T_4 s)}{s(1+sT_5)(1+sT_6)}.I(s) \qquad (7)$$

Where: $T_1 \ldots T_6$ are the time constants.

The mechanical torque output T_{mech} of the diesel engine is proportional to the actual fuel flow rate Φ(s), but is delayed by the fuel combustion process time delay T_D. The mechanical torque (mechanical power) output of the diesel engine is:

$$T_{mech} = e^{-sT_s}\Phi(s) \qquad (8)$$

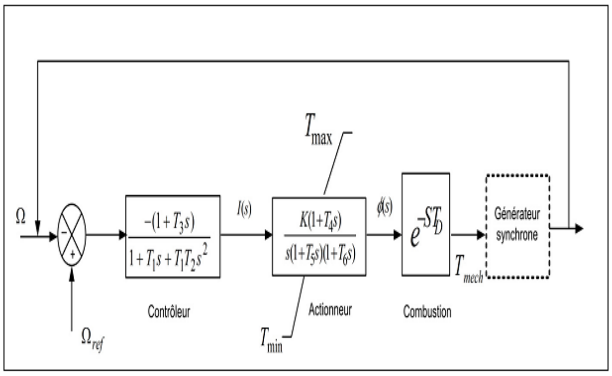

Fig 5: Simplified diesel engine block diagram

4.2.2 Synchronous generator model

The equivalent model of a winding of the synchronous generator is shown in Figure 6 [18]:

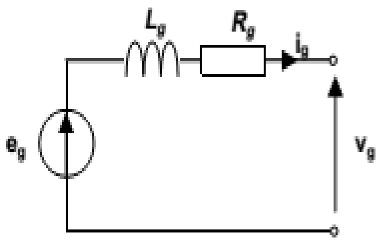

Fig 6: Equivalent model of a winding

Three phase stator has three windings and therefore three electromotive forces eg_1 (t), eg_2 (t) and eg_3 (t) of the same root mean square (rms) value E and phase shifted by $2\pi / 3$.

The Kirchhoff's voltage law to the diagram in Figure 6 is:

$$e_g = v_g + L_g \frac{di_g}{dt} + R_g i_g \tag{9}$$

In the simplified model of the synchronous machine, the mechanical part without friction is described by Eq. (10):

$$J_{ds} \frac{d\Omega_s}{dt} = T_d - T_{em} \tag{10}$$

Where:

J_{ds}: is the total inertia of the entire diesel engine synchronous generator.

Ω_s: is the rotation speed.

T_d: is the mechanical torque on the shaft.

T_{em}: is the electromagnetic torque.

4.3 Modeling of battery storage system

In this work, it was developed a model of the Ni-MH electrochemical battery, the equivalent circuit of the battery storage system can be represented as in Figure 7, [19]:

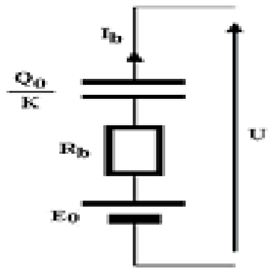

Fig 7: Electrical equivalent model of the battery

The mathematical model given by Eq. (11) that best describes the physical phenomenon of the charge and discharge is given below:

$$U = E_0 - K.\frac{\int I_b.dt}{Q_0} - R_b.I_b \tag{11}$$

U is the voltage across the battery; $\mathbf{E_0}$ is the open circuit voltage of the charged battery, a constant **K** which depends on the battery, the internal resistance $\mathbf{R_b}$ of the battery, the discharging current $\mathbf{I_b}$, Q_0 is the ability of the battery (Ah), $\frac{\int I_b.dt}{Q_0}$ shows the discharge state of the battery.

5. RESULTS AND DISCUSSION

The block Simulink of the isolated hybrid wind-diesel generation system with the proposed DCS is shown in Figure 8. Some of the components described before are blocks which belong to the SimPowerSystems library for Matlab-Simulink.

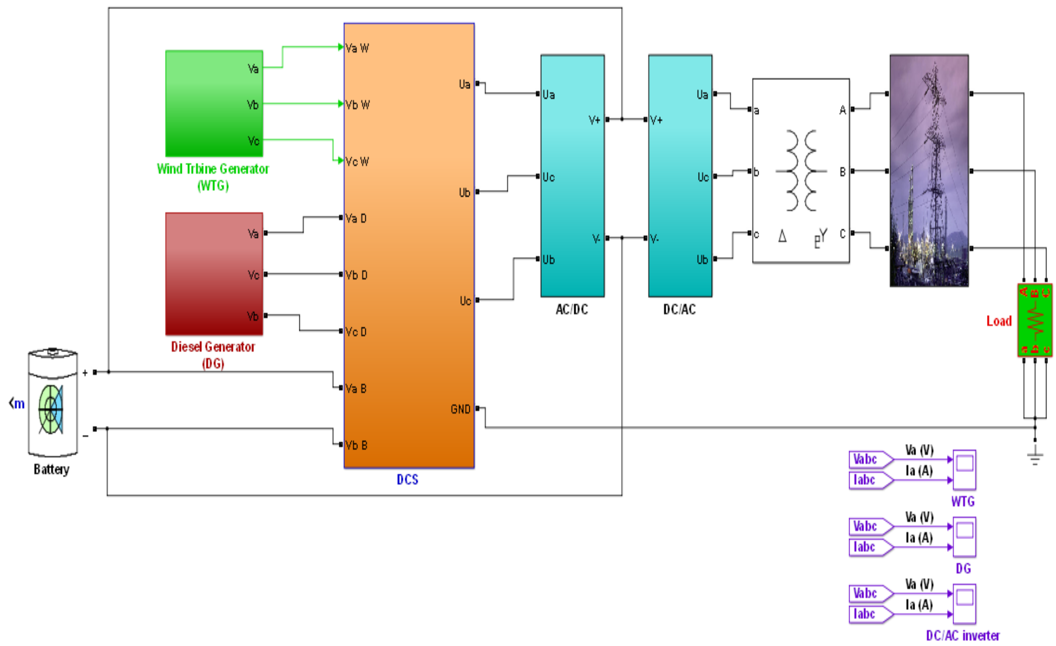

Fig 8: Global model Simulink of autonomous hybrid power system

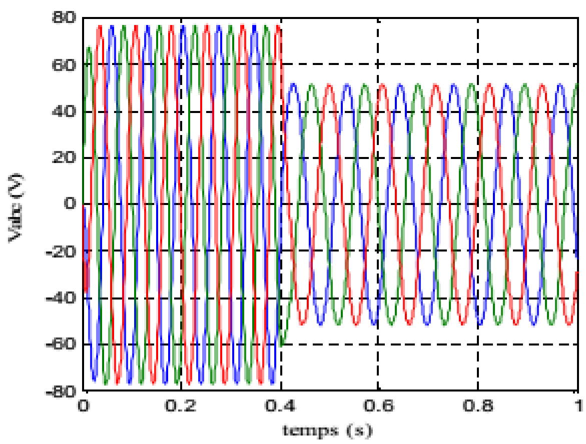

Fig 9: Three phase voltage generated by WTG

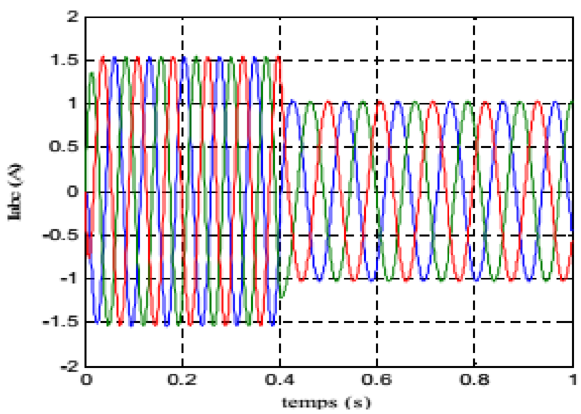

Fig 10: Three phase current generated by WTG

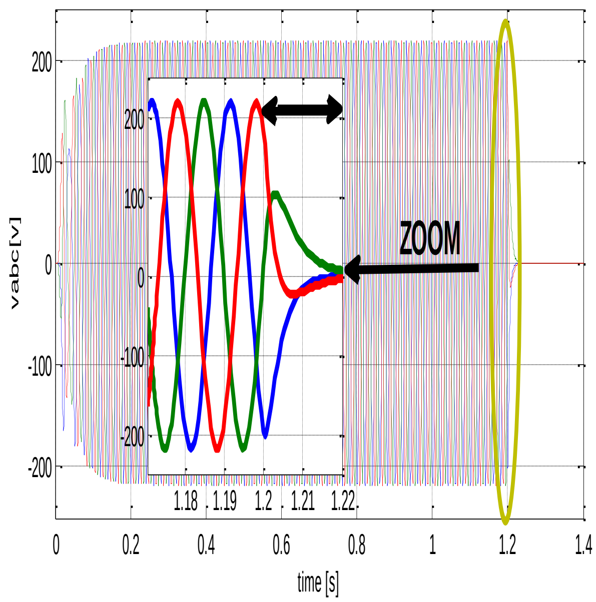

Fig 11: Three phase voltage generated by DG

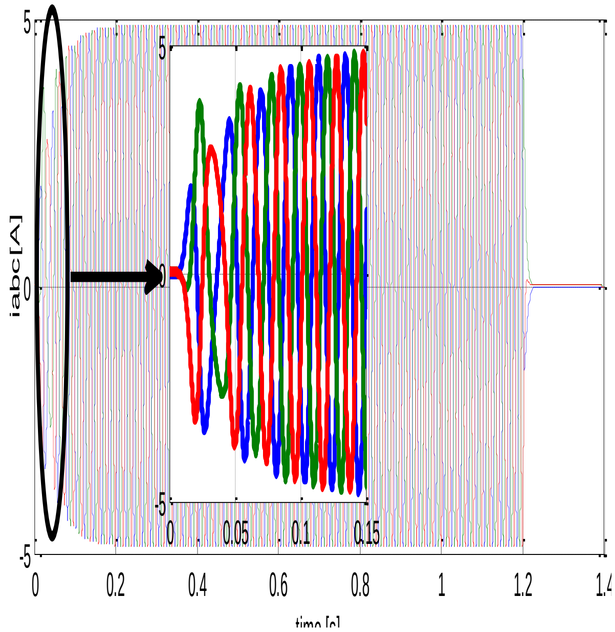

Fig 12: Three phase current generated by DG

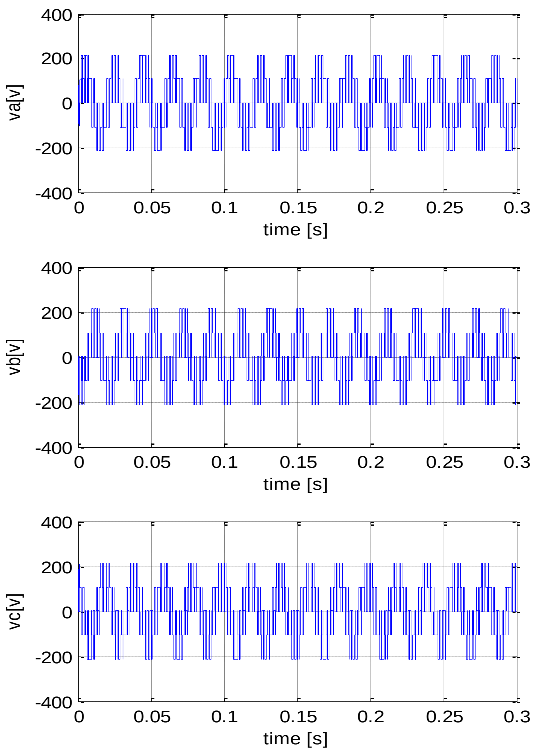

Fig 13: Output voltages of the DC/AC inverter

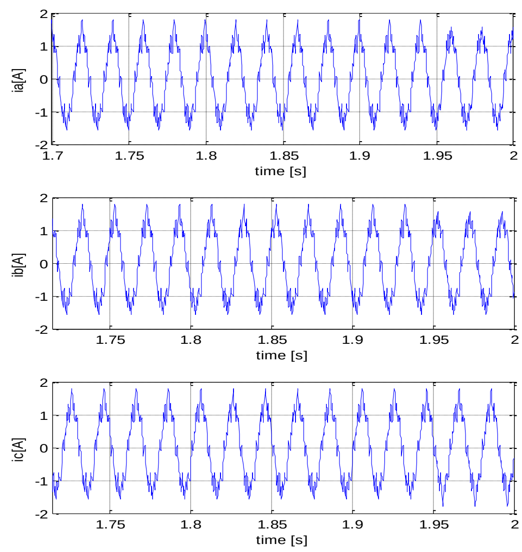

Fig 13: Output currents of the DC/AC inverter

6. CONCLUSIONS

This paper investigates the modeling and simulation of a wind-diesel hybrid power system for isolated areas. The simulation based on real meteorological data. The global model modeling of hybrid system is based on control strategy to optimize the power output, regulate voltage and frequency transmitted to consumers. The wind-diesel hybrid system used a high control strategy for the management of different power sources (Wind, Diesel, Battery), which ensures the opening\closing different power switches according to meteorological conditions (wind speed). Thus the simulation models for the WDHS were developed and assembled a library of parametric models in the MATLAB/Simulink environment.

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