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Modelling, design and control of wind diesel hybrid power system using bond graph

Badoud Abd Essalam[#1], Khemliche Mabrouk[#2] and Raison Bertrand[*3]

[#] *Automatic laboratory of Setif, Electrical engineering department, university of Setif 1, City of Mabouda, Setif Algeria, 19000*

[1]badoudabde@yahoo.fr

[3]mabroukkhemliche@yahoo.fr

[*] *G2ELab, Grenoble Institute of Technology, Domaine Universitaire, 11 Rue des Mathématiques, BP 46, 38402 Saint-Martin d'Heres, France*

[2]bertrand.raison@g2elab.inpg.fr

***Abstract*— This paper illustrates the use of diesel electricity generator set and Dispatch Controller to adapt the number of running engines to a given electrical load that is partly met by wind turbines. Control coordination among the system components is established with a view to regulate the system voltage and frequency while extracting maximum power from wind. This paper utilized the bond graph approach in the modeling of such a wind/diesel hybrid power system for a stand-alone unit in a remote location. This design allows for the addition of wind energy inputs in conjunction with the diesel generators for fuel saving.**

***Keywords*—Hybrid System, Wind–Diesel Systems, Modelling, Bond Graph, Optimization**

I. INTRODUCTION

The pressing need to utilize all abundant renewable green energy sources (Wind, Solar, PV, Wave, Tidal, Fuel Cell, Hybrid ...) is motivated by economic and environmental concerns. The increasing reliance on costly fossil fuels with increasing rate of resource depletion is causing a shift to energy alternatives, clean fuel replacement and energy displacement of conventional sources to new green renewable, environmentally safe and friendly counterparts [1-2].

Wind energy is used widely in modern electrical systems either as stand-alone applications or utility connected power stations. In many applications the wind energy systems are combined with other energy system such as fossil energy. For utility-scaled sources of wind energy, a large number of wind turbines are usually built closer to form a wind-Farm.

This paper focuses on small isolated hybrid power system that utilizes a combination of wind turbine and a diesel generator in a typical standalone scheme capacity usually ranging in sizes from 15 KW to 1500 KW [3-4]. Typical applications include electricity supply to remote (isolated Islands/villages, heating, water pumping, ventilation and air conditioning systems.

For a standalone wind energy scheme, the induction generator terminal voltage and frequency are totally dependent on the rotor speed, shunt capacitance size and the electrical load equivalent impedance, which are subject to both wind gusting and dynamic electric load excursion/changing conditions [5]. Such low-cost scheme is usually used in combined passive/motorized loads for driving water pumps/ventilation and air circulation/air conditioning loads, which are generally insensitive to small frequency variations [6-7]. The diesel driven synchronous generator provided a smooth AC output, whereas the output power of the wind turbine generation depended on the wind velocity.

The control of the voltage and frequency of a weak autonomous wind-diesel system is more challenging than in large grids. Bhatti et al. [8] suggested a PI load frequency controller to be installed on the diesel unit to generate command signals to raise or lower the speed-gear ratio in response to the error in frequency. Kamwa [9] studied the dynamic modelling and control of wind-diesel systems by having a programmable smoothing-load controlled by a standard PID regulator installed on the diesel unit. He [10] approached the control problem on two levels: a high level dealing with the total energy of wind turbines, diesel generators, storage and dump load; and a low level containing three independent controllers which determine, respectively, each wind turbine state and power dispatch. Jeffries [11] developed a dynamic model for a no-storage wind-diesel system and validated its components by comparing the simulation results with experimental data. Papathanassiou and Papadopoulos [12] studied the dynamics of a small autonomous wind-diesel system using simplified models and classic control theory techniques. Other control applications of fuzzy logic to power systems and synchronous machines have also been reported [13-15].

In recent years, neuro-fuzzy models of engine processes serve as the basis for model-based methods for simulation, prediction, control and diagnosis [16], [17]. In this work, we develop an algorithm to control through a bond graph, having for objective to improve the performances of the control. This work proposes a full detailed bond graph modelling and a novel control scheme of a wind-diesel hybrid system.

II. INTEGRATED WIND-DIESEL HYBRID SYSTEM

The system under consideration is shown in Fig.1. It consists of a wind source connected to an ac busbar in parallel with a diesel-generator set consisting of a 0.5 MW turbocharged diesel engine driving a synchronous generator. The two generators serve the electrical load in parallel and the control of voltage and frequency is maintained by the diesel-generator set.

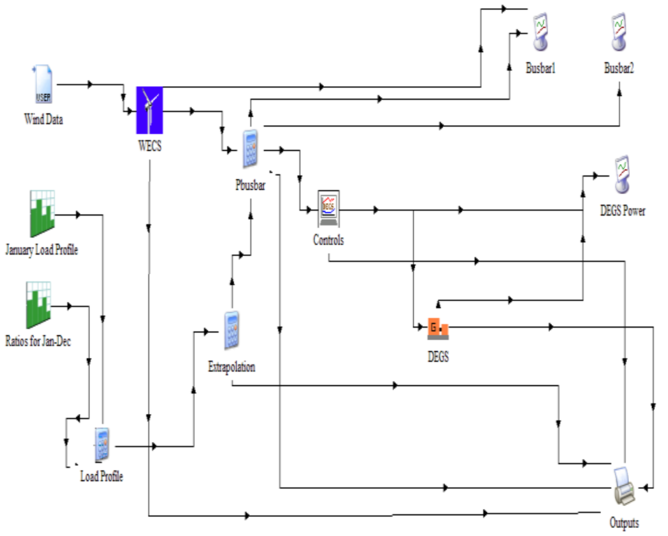

Fig. 1 Proposed hybrid RAPS system

A. *Diesel Generator*

From an electrical system point of view, a diesel generator can be represented as a prime mover and generator. Ideally, the prime mover has the capability to supply any power demand up to rated power at constant synchronous frequency. The synchronous generator connected to it must be able to keep the voltage constant at any load condition. When power demand fluctuates the diesel generator could vary its power output via fuel valve regulation and governor control.

B. *Wind Turbines*

Larger isolated AC electrical systems can use wind turbines of the he type connected to large central grids. The turbines are typically 10 kW to 500 kW. Most of the wind turbines (WT) larger than 50 kW use induction generators. They turn at a nearly fixed speed, based on the frequency of the AC network to which they are connected. They also require an external source to supply their voltage requirements. Thus, in hybrid power systems they operate only when at least one diesel generator is operating.

III. ECONOMIC DISPATCH

Economic dispatch is the process of allocating the required load demand between the available generation units so that the cost of generation is at a minimum. The cost function for each generator can be given by a quadratic function [18]:

$$C_i = a_{i0} + a_{i1}P_i + a_{i2}P_i^2 \qquad \text{\$/hour} . \qquad (1)$$

Where the coefficients ai0, ai1 and a_{i2}, i = 1, 2,.., n assumed to be numerically known. In order to have a quadratic function the property $a_{i2} > 0$, i = 1, 2, …, n must be satisfied [8]. However, the realistic equations for the two diesel generators could not be obtained from the specification sheets of any available generators. Hence, it was taken from Reference [19] where it is then converted to the appropriate cost function equation as shown in Equation 2 below.

$$C = 2.93E-03 + 2.99E-04P_1 + 1.81\text{E-}07P_1^2 \qquad \text{\$/hour} \qquad (2)$$

IV. MODELING OF WIND-DIESEL HYBRID POWER SYSTEM

Hybrid system model can be easily obtained by combining the turbine model and the diesel model. Therefore for the event that there are g diesel generators available and h wind turbines available operating within ith wind speed frame, the remaining capacity and the corresponding probability are given by:

$$C_{RDWi} = C_{RD} + C_{RWTGi} \qquad (3)$$

$$P_{DWi} = P_D . P_{WTG} . P_{Wi} \qquad (4)$$

The following subsection presents the development of a model for each component of the hybrid system, and explaining on the construction on the bond graph elements.

A. *Wind Turbine Model*

In the designing of a wind turbine model, a couple of factors that are important are the availability of the wind and the power curve of the wind turbine itself. The wind turbine model consists of the aerodynamic model, the WT drive train model, and the induction generator model. In the aerodynamic model the blades are assumed to be infinitely rigid in the frequency range of interest. Therefore, a simplified model is used with average wind speed $\upsilon_\omega(m/s)$ as input. The aerodynamic power is calculated as:

$$P_\omega = \frac{1}{2} C_p \rho A_r \upsilon_\omega^3 \qquad (5)$$

Where $\rho(Kg/m^3)$ is the air density, $A_r(m^2)$ is the swept area of the rotor, $\upsilon_\omega(m/s)$ is the wind velocity, and C_p is the power efficiency coefficient which is a function of tip speed ratio λ and blade pitch angle β. The tip speed ratio is defined as:

$$\lambda = \frac{\omega_t r}{\upsilon_\omega} \qquad (6)$$

$r(m)$ is the radius of the blades and $\omega_t(rad/s)$ is the wind-turbine speed. The mechanical rotor torque is given by:

$$T_\omega = \frac{\rho_\omega}{\omega_t} = \frac{1}{2} C_p \rho A_r \frac{\upsilon_\omega^3}{\omega_t} \qquad (7)$$

The inputs of the model are the wind speed υ_ω and the mechanical rotational speed ω_t. The outputs from the model are the aerodynamic power $\rho_\omega(W)$ and the mechanical rotor torque $T_\omega(N.m)$ which will act on the drive train.

In the WT drive train model, the mechanical torque T_ω acts on a rotor with a moment of inertia $J_t\left(Kg.m^2\right)$. The rotor is attached to the main low speed shaft through a flexible coupling. The generator is connected to the main high-speed shaft and the gear is modeled as an ideal transmission. The inputs of the model are the mechanical torque T_ω from the aerodynamic model and electrical torque T_a from the generator. The outputs of the drive train are the wind-turbine speed, ω_t, and the generator-rotor speed, ω_a.

Figure (2) presents the bond graph model of the turbine.

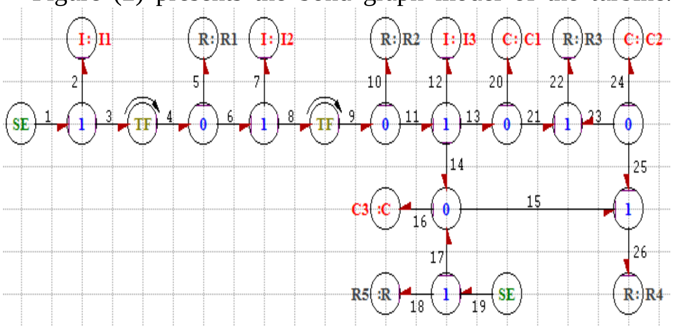

Fig. 2 Bond graph model of turbine

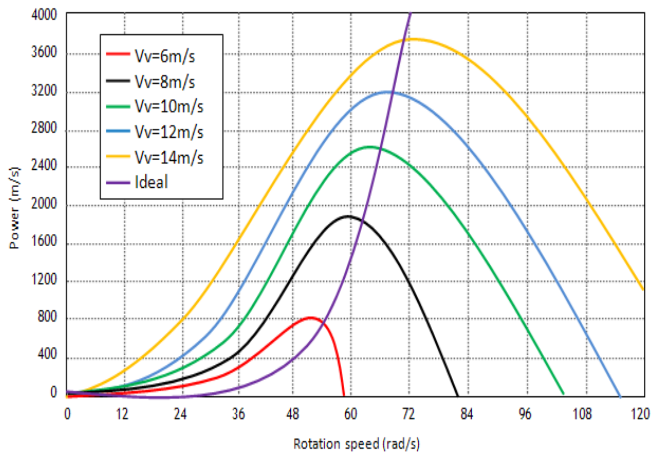

Fig. 3 Power versus rotor speed of the turbine at various wind speeds

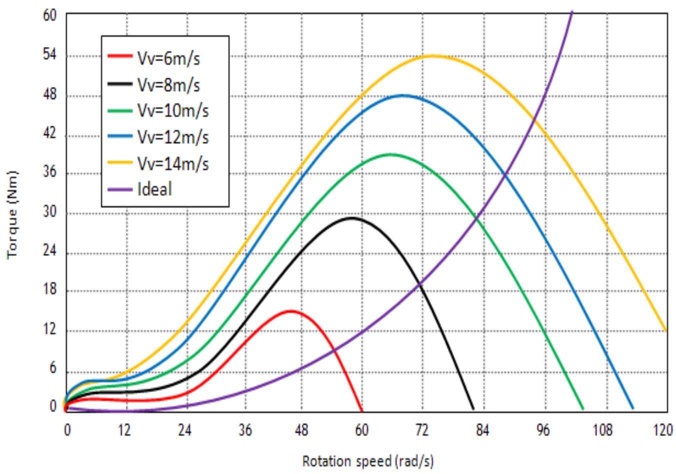

Fig. 4 Torque versus rotor speed of the turbine at various wind speeds

The objective of this part is to model the wind generator. The structure of selected wind mill has already been the subject of several studies [20], [21], [22] which resulted in developing the test bench in order to validate the control developed strategies. The level of modeling sought for the turbine must enable us to apprehend them electric phenomena.

B. Diesel engine model

The diesel engine model gives a description of the fuel consumption rate as a function of speed and mechanical power at the output of the engine [23]. The diesel engine is usually modeled by a simple first order model relating the fuel consumption (fuel rack position) to the engine mechanical power. The efficiency of the combustion ε is the ratio of the effective horsepower developed by the engine and available on its crankshaft to the heat consumed during the same time, i.e.,

$$\varepsilon = \frac{zW_i\upsilon}{\overset{*}{m}_f\ HHV} \tag{8}$$

Where $HHV\ (KJ/Kg)$ is the higher heating value of the biogas, $\overset{*}{fm}\,(Kg/s)$ is the combusted fuel rate, υ is the stroke cycles per second, $W_i\,(KJ)$ is the mean effective work (developed by one piston during a combustion cycle) and z is the number of cy1inders (operating during a combustion cycle). Incomplete combustion is the main reason for which the indicated efficiency is lower than the ideal efficiency. The mean effective pressure $P_i\,(Pa)$ of the engine is defined as

$$P_i = \frac{W_i}{V_h} \tag{9}$$

$V_h\left(m^3\right)$ is the diesel engine one stroke volume. By solving (8) with respect to W_i and substituting into (9) we get

$$P_i = \frac{HHV}{zV_h\upsilon}\overset{*}{m}_f\ \varepsilon \tag{10}$$

Note that for normal or stable power system operation υ is almost constant and its value is imposed in order to keep the system frequency constant at 50 Hz. Mechanical losses are expressed as equivalent pressure droop (Pa). This mean pressure of mechanical losses P_f is taken in a first approximation proportional to the mean piston speed U_d. The real mean effective pressure P_k of the engine must be

$$P_k = P_i - P_f \tag{11}$$

The real mechanical power P_{Dm} of the diesel engine is given by the equation:

$$P_{Dm} = zV_H\upsilon P_k = V_H\upsilon P_k = V_h\frac{\omega_m}{\pi K}P_k \tag{12}$$

Where K is the number of strokes, $V_H\left(m^3\right)$ is the diesel engine total stroke volume and $\omega_m\left(rad/s\right)$ is the diesel engine speed. The mechanical torque $T_{Dm}\left(N.m\right)$ of the engine is then given by the following relation in the p.u. system:

$$T_{Dm}=\frac{P_{Dm}}{\omega_m T_b}=\frac{V_H P_K}{\pi K T_b} \qquad (13)$$

$T_b\left(N.m\right)$ is the base torque for the per-unit transformation. The transfer function of a reciprocating engine involves a small but significant dead time τ_1. This time represents an effective dead time that elapses after a disturbance, before all the engine cylinders fire at a new torque level. The two individual dead times which affect the value of τ_1 are the ignition delay and the power-stroke delay. An expression is given in [24,25] to compute τ_1 with respect to the diesel engine speed variations.

$$\overset{*}{m}_f(t)=\overset{*}{m}_B(t-\tau_1) \qquad (14)$$

$\overset{*}{m}_B(Kg/s)$ is the diesel engine consumption rate. The bond graph model of diesel generator is shown in figure (5).

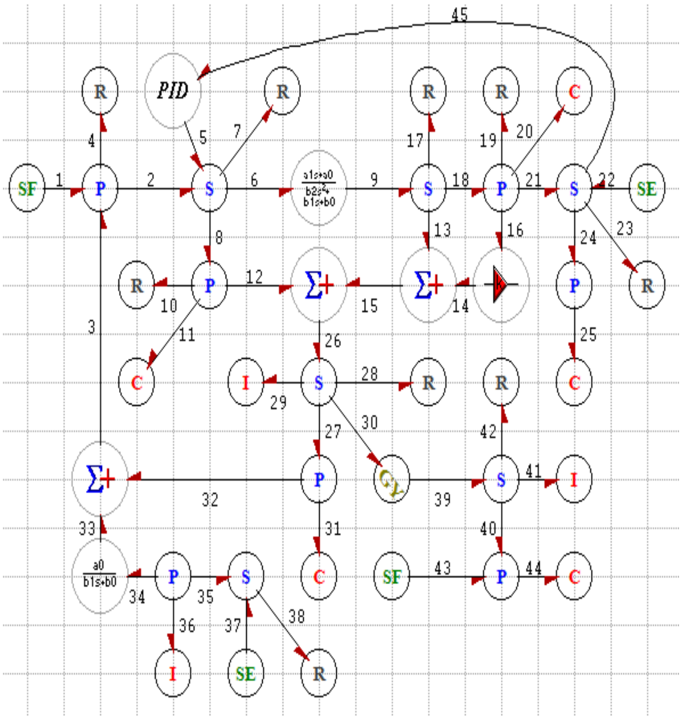

Fig. 5 Diesel generators model

V. Bond Graph Controller

From a control point of view, the wind-diesel plant considered in this study has an operating point that is continuously changing due to the natural fluctuation of available power from the renewable energy source. A linear controller designed to work optimally around a nominal operating point of a non-linear system may be degraded at other operating points.

Bond graph controller is very attractive for ill-defined systems or systems with uncertain parameters. With the help of Symbols code, expert's knowledge can be used directly to design a controller. Bond graph allows one to express the knowledge with subjective concepts such as very big, too small, which are mapped to numeric ranges.

The bond graph methodology provides a particularly formalism to represent the energy transformations in the heterogeneous systems because of its unifying character with respect to the various fields of physics [26], [27], [28] based on the energy exchange between under systems; it is a power transfer . It is very simple to specify on a model bond graph the causal relations between the signals associated with the physical magnitudes with the system. Once causality is assigned, we can derive directly from the bond graph of the very current causal models in the automatic.

The basic elements contain elements without temporal aspect (R element for losses, TF-element for transmission between two flows, Gy- element transmission between an effort and a flow), elements with a temporal aspect (I element for kinetic accumulation energy, C-element accumulation potential energy) and elements of source (SE effort source, SF flow source). Different systems can be represented by bond graph. From the model it is possible to find the transfer function of a system, which helps to develop the structure of the order.

The proposed algorithm was validated by means of simulations performed with the Symbols code in two different situations, the former assuming the presence of the proposed control system and the latter its absence.

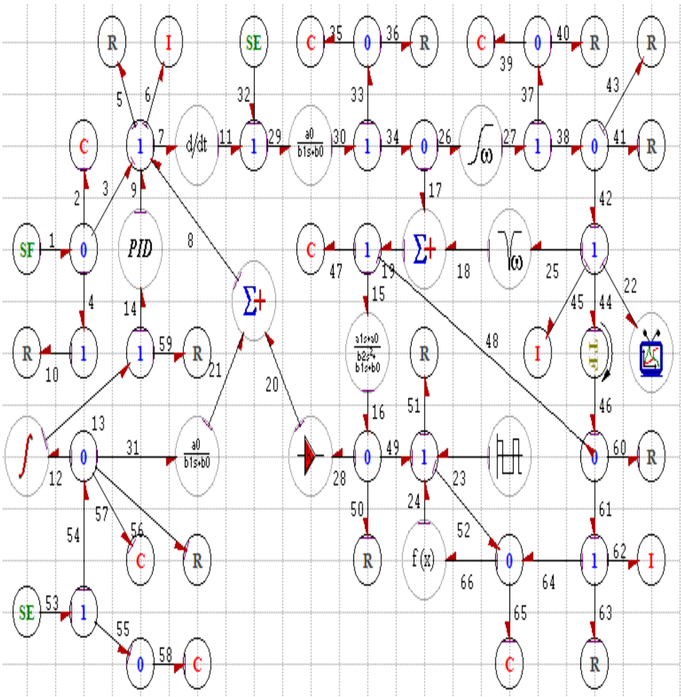

Fig. 6 Bond graph controller

VI. SIMULATION RESULTS

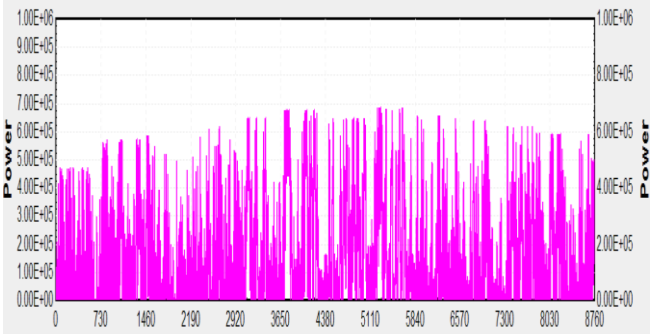

Fig. 7 Power P_{WECS}

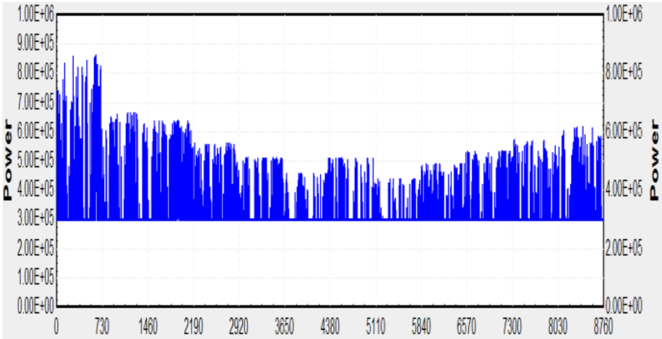

Fig. 8 Power P_{DEGS}

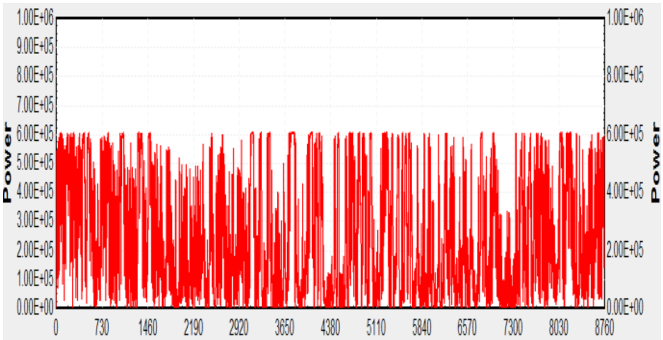

Fig. 9 Power P_{dump}

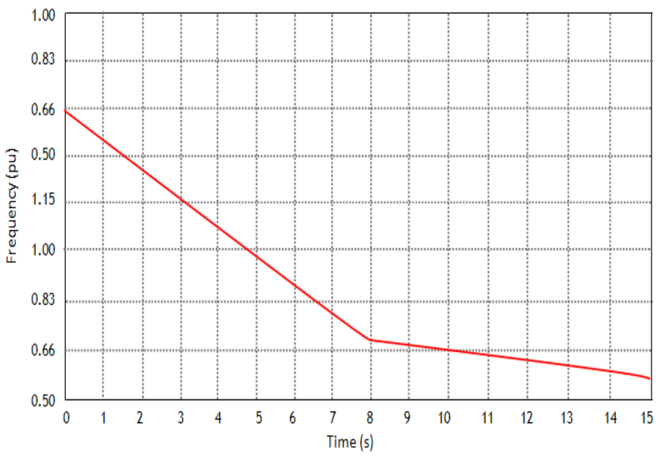

Fig. 10 Frequency at Load terminals (System operating without frequency controller)

Figure (10) the variation in frequency to simulation time. It is observed that the system is not stable as the frequency is dropped to very low value which is beyond the permitted limits.

The effect on the other power quality parameters is almost negligible as only disturbance incorporated is wind variations. The second set of readings is taken with governer controller and excitation controller in the system.

The parameters i.e. K_i, K_p, K_d for PID controller used in governer control are randomly chosen as k_i=75, k_p = 0.03 and k_d = 85.

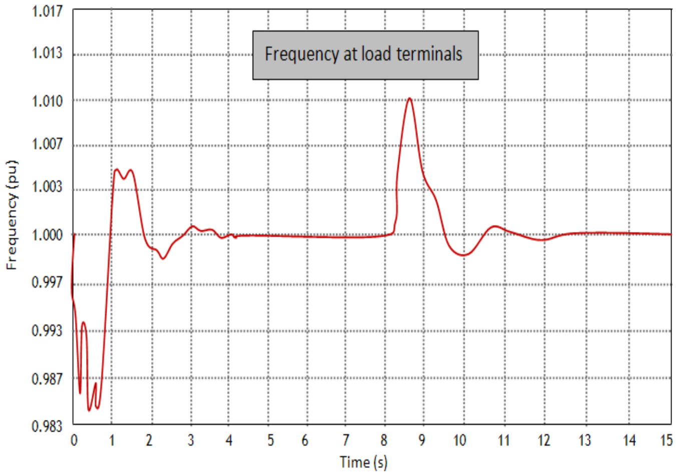

Fig. 11 Frequency at Load terminals (Randomly selected PID controller parameters)

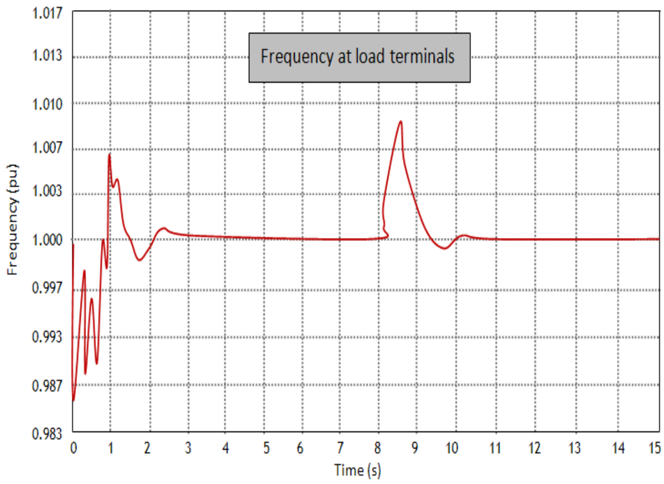

Fig. 12 Frequency at load terminals (optimized controller parameters).

Figure (11) shows the variations in frequency when wind speed changes from 6 m/s to 8 m/s at the instant of 8 sec.

Using optimized PID gains the variation in frequency is shown in figure (12). The change in frequency at 8 sec (instant of disturbance) is recorded and it is observed that the maximum variations recorded in the frequency at load terminals are 1.009 pu to 0.999 pu after the disturbance which is less than the variations as obtained with randomly selected gains. The settling time of the disturbance is also reduced to 2 sec from 4 sec.

VII. CONCLUSION

This paper has investigated the hybrid operation of a novel hybrid wind-diesel remote area power system. The system performance has been investigated in relation to the bandwidth of the voltage regulation capability under variable load and wind conditions.

The objective of this paper is to show that the bond graph rest on solid mathematical bases which make it possible to consider applications on a large scale, in particular in modeling. If the resolution of complicated problems always requires and will still require very a long time, much of work and a wide range of knowledge in statistics, treatment of the signal, automatic,... it is not doubtful that the bond graph can reduce considerably the task of the engineers by allowing an effective and generic approach nonlinear problems

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