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Dynamic Modelling and Optimal Sizing of Stand-Alone Hybrid Wind/Diesel Power Generation System

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ABSTRACT

This paper recommends an optimal sizing model, to optimize the capacity sizes of different components of hybrid wind-diesel power generation systems. The recommended model takes into account the sub-models of the hybrid system. 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.

Key words: Bond graph modeling, sizing, Wind/diesel hybrid system, Power generation

INTRODUCTION

Power networks at remote areas that use conventional energy sources such as diesel often face particularly high fuel transportation and environmental costs [1-2]. With the rapid development of photovoltaic, wind turbine and battery technologies, hybrid energy system has received increasing attention as an alternative to conventional system, with diesel generation only as emergency backup [3]. 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 (diesel). For utility-scaled sources of wind energy, a large number of wind turbines are usually built closer to form a Wind-Farm.

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 specially 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.

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 [4-5]. Typical applications include electricity supply to remote (isolated 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 [6]. 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 [7-8]. The diesel driven synchronous generator provided a smooth AC output, whereas the output power of the wind turbine generation depended on the wind velocity.

In this paper, a simulation and bond graph model of standalone wind energy conversion system combined with a diesel engine based power generation system is introduced. The wind energy conversion system is developed with maximum power point tracking MPPT control, power electronic interface and voltage regulators. A diesel power generator is connected with the system due to random nature of renewable energy sources. Frequency regulation is controlled by a simple discrete threephase locked loop (PLL) control strategy along with resistive dumping load.

WIND-DIESEL HYBRID SYSTEM

The hybrid generation system is composed of a wind turbine generator (WTG), diesel generator (DG), 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. The DC and AC filter compensator schemes are used to ensure stable, efficient, minimal inrush operation of the hybrid DC-AC renewable energy scheme.

Modelling 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:

$$C_{RDWi} = C_{RD} + C_{RWTGi} \quad (1)$$

$$P_{DWi} = P_D.P_{WTG}.P_{Wi} \quad (2)$$

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

Wind Bond Graph Modelling

Wind speed estimation is highly important so as to determine the electric power to be supplied from wind power or wind [9]. It maintains a direct relation to the torque over the turbine axis and therefore it may also have some direct effect on the power output of the wind turbine generation system (WTGS) hence its evolution must be taken into account to properly simulate the WTGS dynamics. Wind speed varies from one location to another and also fluctuates over time. The evolution of the wind speed according to time is modeled by a bond graph model starting from the data of measurement for a given site. In a context of theoretical modeling; the profile of wind must satisfy 2 criteria: the duration of the profile must be limited to reduce the time of simulation and the profile of wind must be representative of the characteristics layer.

The wind speed can thus be modeled as a scalar function which evolves in time (figure 2)

$$V = f(t) \quad (3)$$

In this study, we represented the speed wind evolution of the deterministic way, by a sum of several harmonics as indicates the bond graph model following (figure 3):

$$V_{wind}(t) = V_0\left(1 + \sum A_k \sin\left(w_k.t\right)\right) \quad (4)$$

V_0 is a value of wind velocity; Ak is amplitude of harmonic; wk is frequency of harmonic.

Figure (4) presents a wind profile reflecting the stochastiquity. It is a profile filtered and adapted to our studied wind system which has a slow dynamic [10].

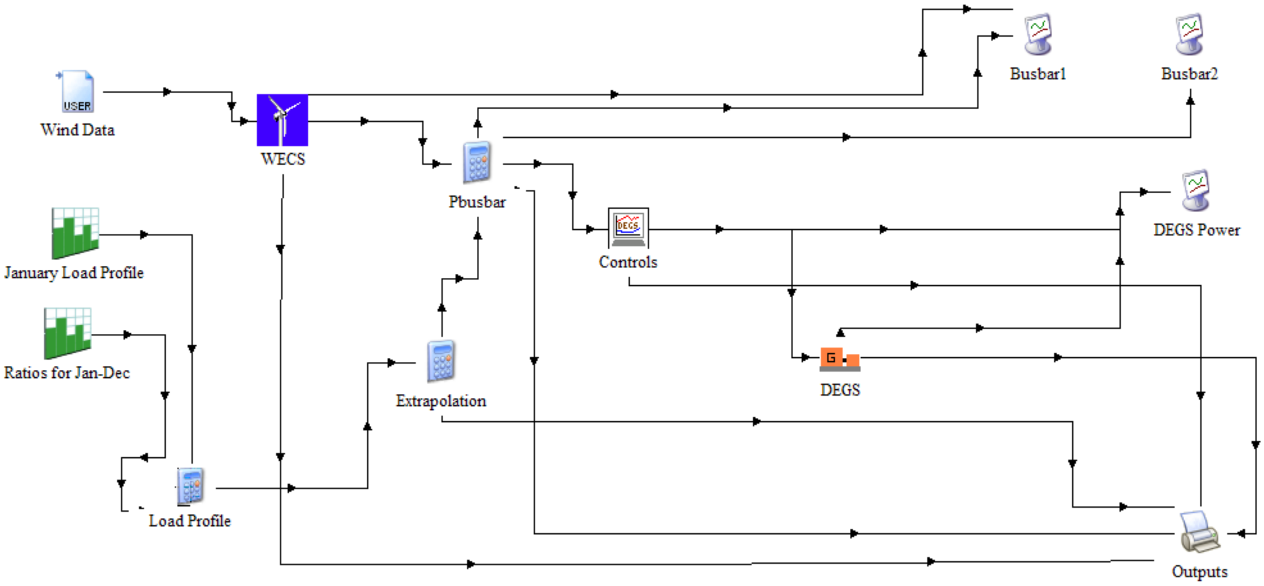

Fig.1 Proposed hybrid RAPS system

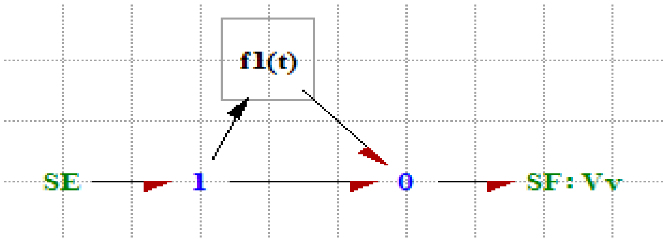

Fig. 2 Bond graph model of wind speed

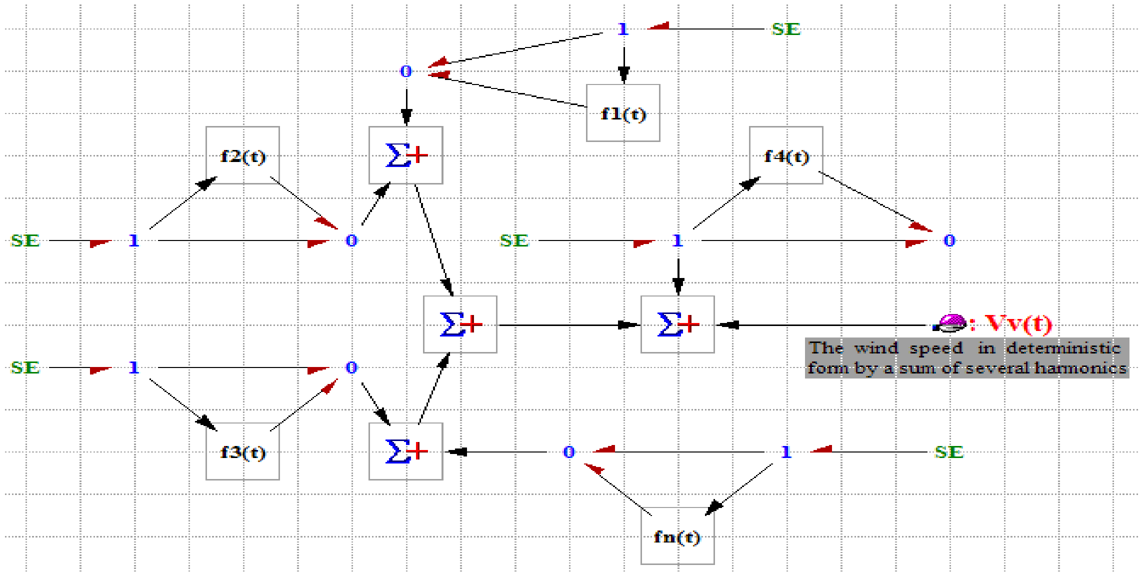

Fig. 3 Bond graph model of wind speed of the deterministic way by a sum of several harmonics

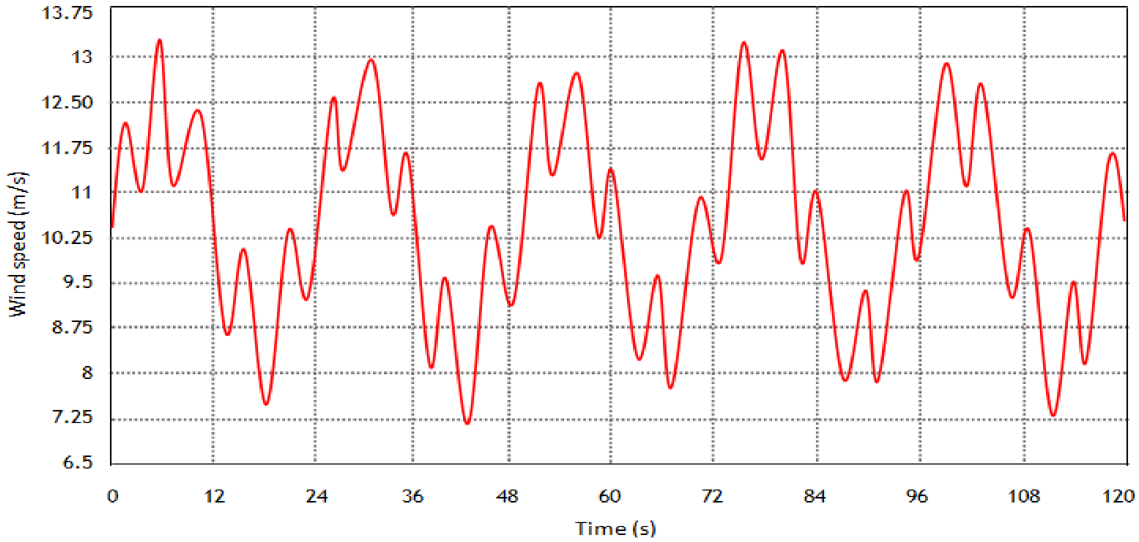

Fig. 4Profile filtered wind

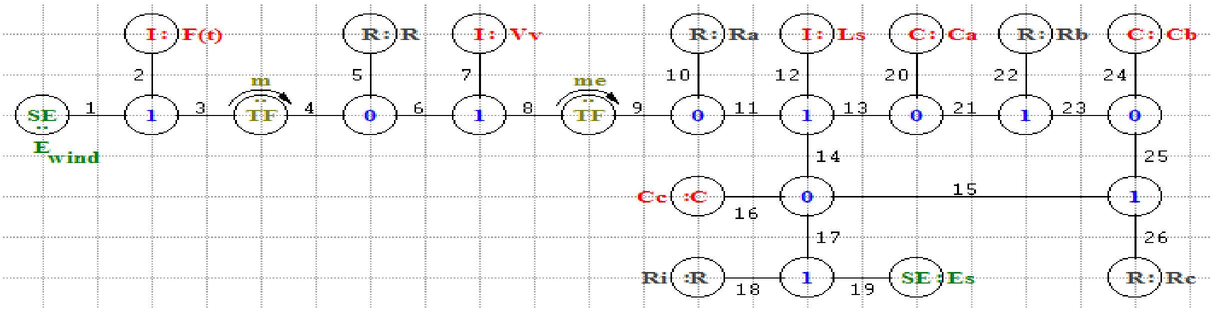

Fig. 5 Bond graph model of wind turbine

Wind Turbine Bond Graph Model

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.

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 $\upsilon_\omega\left(m/s\right)$ as input. The aerodynamic power is calculated as:

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

Where $\rho\left(Kg/m^3\right)$ is the air density, $A_r\left(m^2\right)$ is the swept area of the rotor, $\upsilon_\omega\left(m/s\right)$ 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:

$$\lambda = \frac{\omega_t r}{\upsilon_\omega} \tag{6}$$

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

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

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 $\rho_\omega\left(W\right)$ and the mechanical rotor torque $T_\omega\left(N.m\right)$ 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.

Diesel Engine Model

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.

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 [11]. 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 $HHV\left(KJ/Kg\right)$ is the higher heating value of the biogas, $\overset{*}{fm}\left(Kg/s\right)$ is the combusted fuel rate, υ is the stroke cycles per second, $W_i\left(KJ\right)$ 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 $P_i\left(Pa\right)$ 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 (9) with respect to W_i and substituting into (8) 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:

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

$T_b \left(N.m\right)$ 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 [12-13] to compute τ_1 with respect to the diesel engine speed variations.

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

$\overset{*}{m}_B (Kg/s)$ is the diesel engine consumption rate.

The bond graph model of diesel generator is shown in figure (3).

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 [8]:

$$C_i = a_{i0} + a_{i1} P_i + a_{i2} P_i^2 \qquad \text{\$/hour} \tag{15}$$

Where the coefficients a_{i0}, a_{i1} 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 [9] where it is then converted to the appropriate cost function equation as shown in equation (14) below.

$$C = 2.93E-03 + 2.99E-04 P_1 + 1.81E\text{-}07 P_1^2 \qquad \text{\$/hour} \tag{16}$$

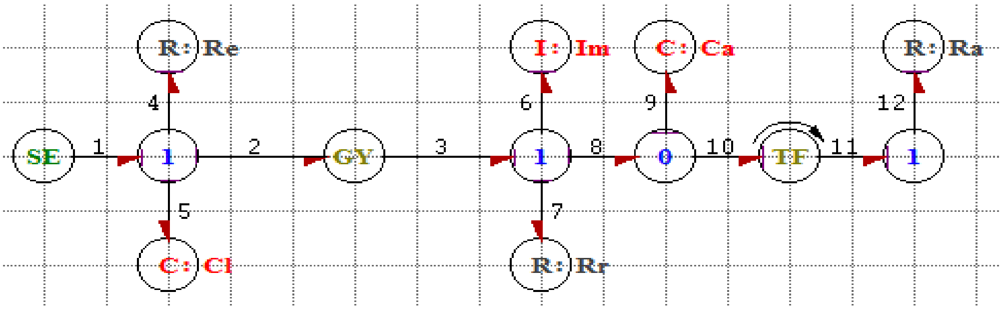

Fig. 6 Bond graph model of diesel generator

RESULTS AND DISCUSSION

Figure (7) 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 governor 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. Figure (8) 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 (9). 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.

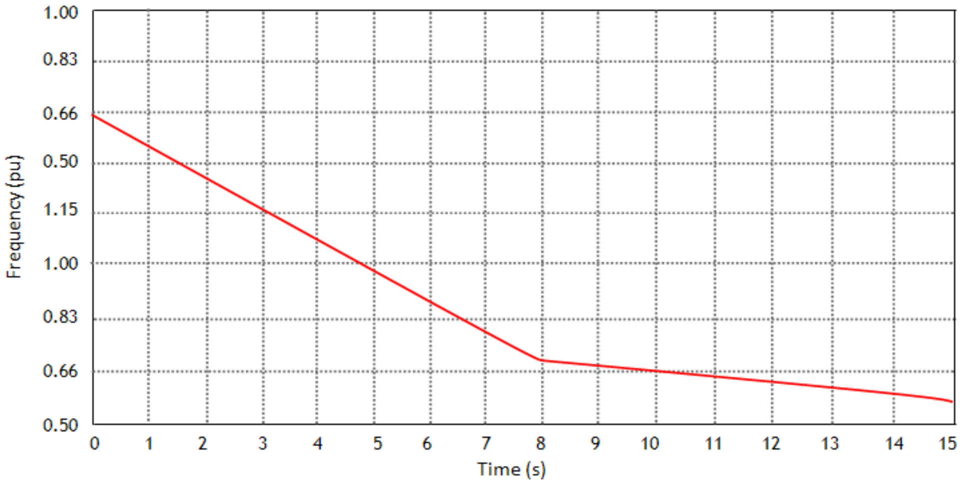

Fig.7 Frequency at Load terminals (System operating without frequency controller)

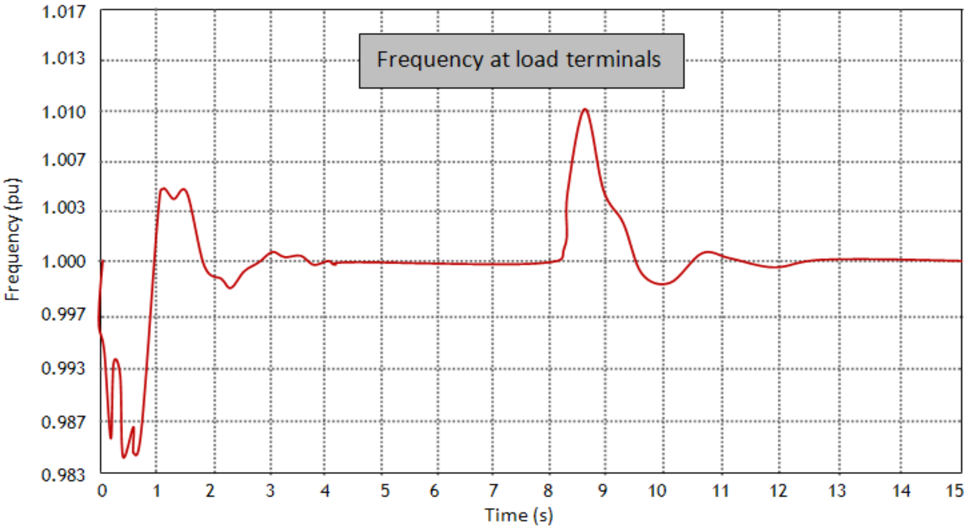

Fig.8 Frequency at Load terminals (Randomly selected PID controller parameters)

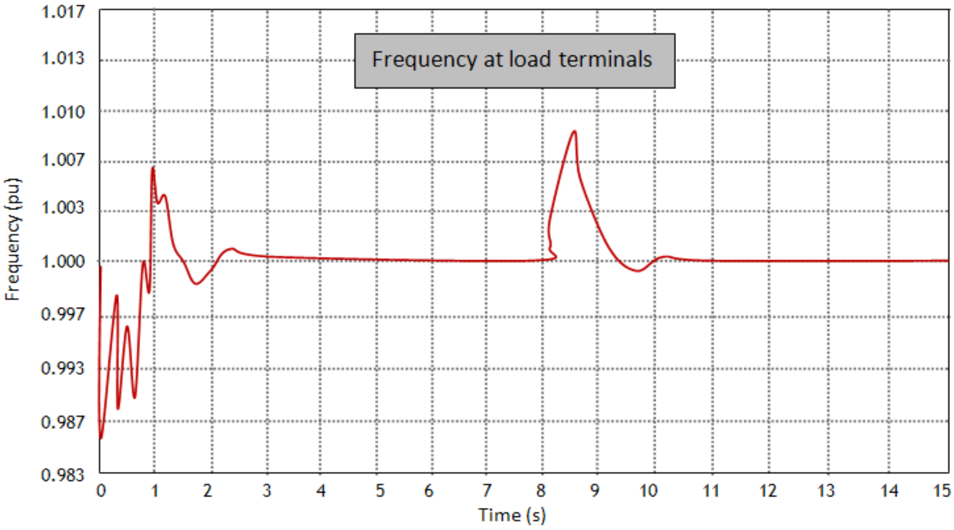

Fig.9 Frequency at load terminals (optimized controller parameters)

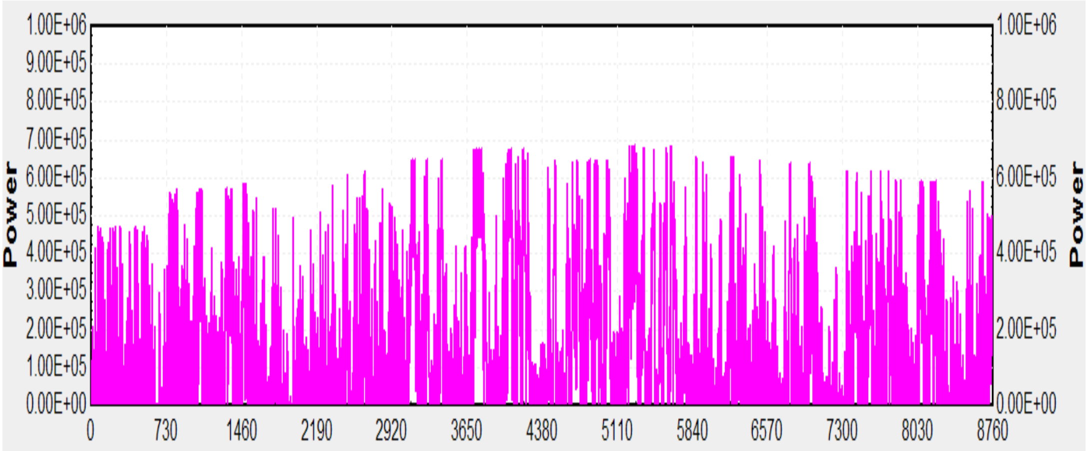

Fig.10 Power P_{WECS}

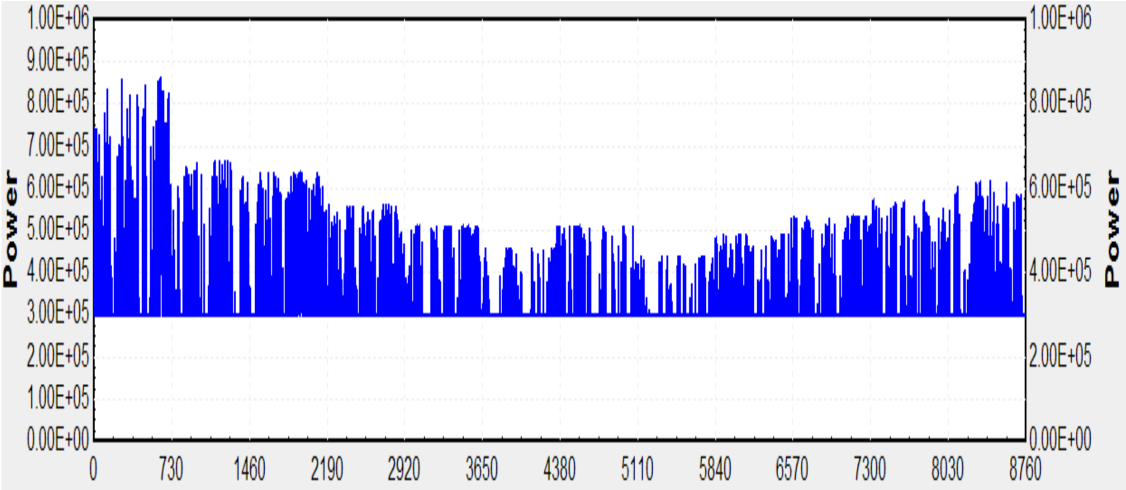

Fig.11 Power P_{DEGS}

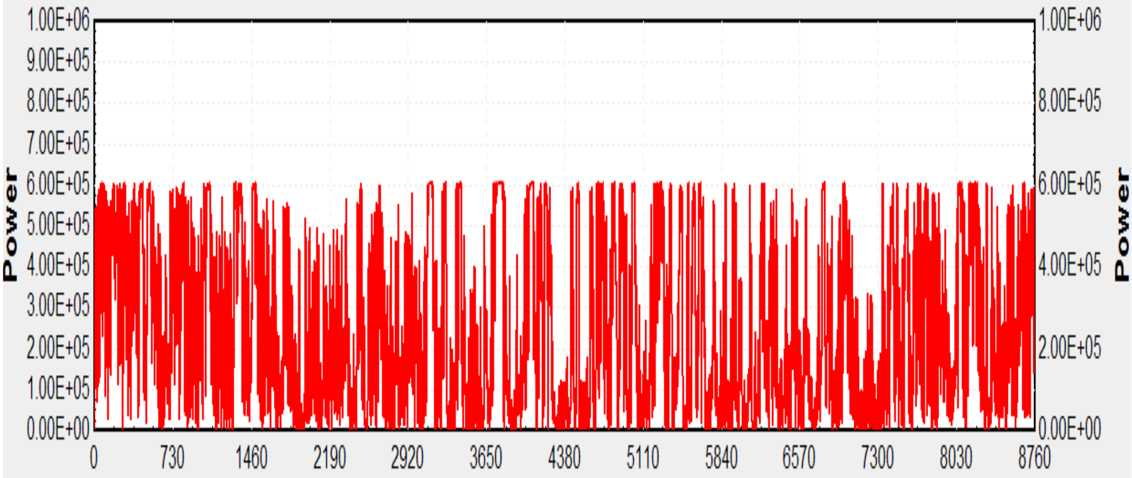

Fig.12 Power P_{DUMP}

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 global model modelling 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, 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 Symbols environment.

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