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# Modeling, Simulation and Dynamic Analysis of An Integrated Autonomous Wind-Diesel Hybrid Power System With No Storage For Uninterrupted Power Applications

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## Abstract

The paper discusses the modeling of an isolated wind-diesel hybrid system (WDHS) with no storage for dynamic performance analysis and the system performances have been validated by simulation in Matlab/Simulink software. WDHS is a potential source of reliable power, where the problem of power unpredictability has been addressed effectively and can be employed even for critical loads. The paper elaborates the structure of the designed power system, the system architecture, the movement of control signals through common communication bus, modeling of all the major components in the system and validates the system performance using simulation software. The simulation results show that under any variation of the wind power, the system readjusts itself in such a way that the system frequency as well as the micro grid voltage is maintained constant at preset values, without diluting the active power flow required for the system. It is evident from the simulation results that the diesel generator provides the necessary frequency and power correction mechanism during low power output stages from the Wind turbine generator and the dump load provides the necessary compensation during high wind conditions for ensuring reliable and quality power in the system.

**Index Terms:** Active Power, Diesel generator, Frequency, Hybrid power system, Simulink, Wind turbine

## Introduction

Wind-diesel Hybrid system (WDHS) consists of wind-turbine (WT) and coupled asynchronous generator, diesel engine (DE) and coupled synchronous generator which forms the Diesel generator (DG), system load consisting of primary as well as supplementary/secondary load (SL), communication networks including system sensors and actuators coupled through the common communication bus, dump load (DL) and the discrete frequency regulator. Reference [1 - 3] details the various challenges and constraints connected with distributed power generating systems for maintaining system stability. One of the key challenges with distributed generation systems in general is the unpredictable nature of the renewable resource availability like wind, sunlight etc and thus to maintain the critical electrical parameters like system frequency and voltage magnitude constant at preset values, on the assumption that the other basic requirement needed for parallel operation of generators are properly met. The output power of WT is a variable quantity, depending on the available wind potential of each instant and the DG should adapt to the different instants for maintaining system stability. Also, the total reactive power supplied by the reactive sources should be absorbed by the cumulative reactive sink, for maintaining system reactive power balance. Another critical situation happens during the abundant wind power flow, in excess of maximum system load, breaking the system power balance thereby creating a sharp increase in system frequency. The rise in the system frequency are detected by the sensor and communicated to the actuator system for introducing the DL, virtually increasing the system load and restores the system frequency. Several articles are cited in references which are designed to give solution to various issues of WDHS. References [1], [2], [4], [8] discuss the various issues encountered with WDHS during several unstable situations. The general power quality issues with hybrid systems are elaborated in article [5]. References [3], [6] describe how battery can be effectively used to overcome the transient stages during high wind conditions of the system. Reference [7] describes the performance investigations of the system with Permanent magnet Induction generator. Reference [9] describes the control strategy of a wind based hybrid power system using doubly fed Induction Generator. Reference [21] describes the application of the permanent magnet synchronous machine based flywheel system for hybrid power application for meeting transient conditions. This paper concentrates on the modeling of an autonomous wind-diesel system which can be modeled to work effectively without any secondary power storages and ensures the stability of system parameters during all transition periods. The various modes of system operation and the system architecture are explained in section 2. The modeling of major system components are explained in section 3. The simulation schematics and the validation of the model are explained in the subsequent sections.

## Operating Modes of WDHS and System Architecture

A WDHS has three modes of operation namely Diesel only (DO) mode, Wind-Diesel (WD) mode and Wind Only (WO) mode [4], [5].

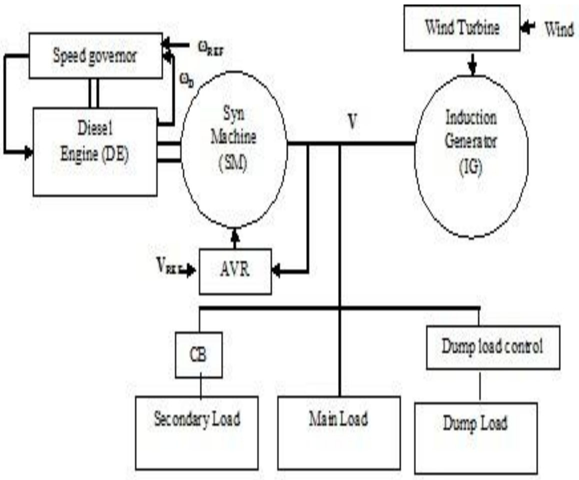

Figure-1 Block diagram of proposed hybrid Wind-Diesel system

In DO mode, the wind potential available for power production is very less and the WT is virtually in the Off stage, as no effective power production is possible. In this mode, the diesel is the only source of active power for meeting the system load. The DG should also provide the necessary source/sink to maintain the necessary reactive power balance in the system. In WD mode of operations, the active power from the WT is inadequate to meet the system load demand. The deficiency in generated power from WT is compensated from the DG. So the combined effort of WG and WT will provide the active and reactive power balance in the system. In WO mode of operation, the generated electric power from WT will be in excess of the load demand, due to high wind availability. This generated excess power will increase the system frequency creating problems to the equipments connected to the system. To avoid this problem, dump loads (DL) have to be introduced to the system corresponding to the magnitude of excess generated power and to bring back the frequency to preset values, by maintaining system power balance. It will also help in avoiding the chances for inverse power flow into the Diesel system.

The communication between various blocks/modules is done with the help of sensor node and communicated to the control units through the communication networks associated with the system.

During the transition from WD mode to WO mode, any deviation of generated system power above the connected load power demand will first be detected by the supplementary load sensors and communicated to the frequency controller. The control mechanism will then introduce the supplementary/secondary Load (SL) to ensure the power balance. The SL rating will normally take as much as 50 percent of PL. However, when the generation exceeds the cumulative Load demand of SL and PL, the excess generated energy will be diverted to DL, which will be communicated through its control signal. The number of DL units to be introduced for effective operation with grid will be communicated from control unit, and is decided based on the amount of excess energy generated during WO mode. It is assumed that the total excess power generated at any instant will always be less than the cumulative rating of all DL units.

The proposed structure of a wind-diesel hybrid model consists of a wind energy conversion system (WECS) and a diesel generator system (DG), a primary and secondary load and a set of dump load (DL) along with its control strategy as shown in Fig-1. The Automatic Voltage regulator (AVR) maintains constant output voltage magnitude and the speed governor will ensure the isochronous operation of DG [11], [19].

## Modeling of Major Components of The System

### A. Wind Turbine

The power extracted by the wind turbine for generating the electric power is a function of cube of the wind velocity. The mathematical model describing the Wind Turbine is given by [16 -18] [23]

$$P_m = \frac{1}{2}\rho\, A\, v^3 C_p \tag{i}$$

where $\rho$ is the air density, $v$ is the wind speed, A is the area swept by the turbine blades and $C_P$ is the power coefficient. $C_P$ is a function of the Tip Speed Ratio (TSR = $R\omega r/v$, where R is the blade length and $\omega_r$ is the WT shaft speed) and the blade pitch. The mechanical torque can be calculated as [6], [16 -17]

$$T_m = \frac{P_m}{\omega_t} \tag{ii}$$

Where $\omega_t$ is the angular rotational speed of the turbine . The realisation of the WT model in Matlab/Simulink is shown in fig 2 [15-16] [23].

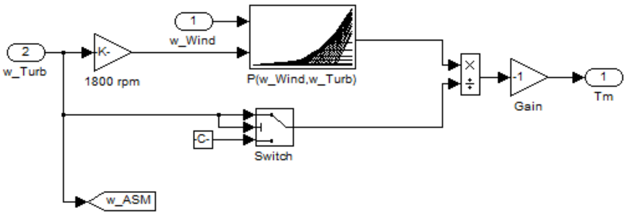

**Figure 2:** Wind Turbine modeled in Simulink

### B. Asyncronous Generator

All the voltage and torque equations that describe the dynamic behavior of an induction motor are time-varying [20-22]. By introducing proper transformation matrix, a new set of variables can be used thereby the complexity of these equations are reduced by eliminating all time-varying inductances, formed as a result of relative motion between stator and rotor fields. By this approach, a set of three variable (a, b, c) variables can be reduced to a set of two phase windings (q-d) which are moving on an arbitrary reference frame [12-14].

The torque equation in terms of flux linkages is given by

$$\mathrm{T_e} = \frac{3}{2}\frac{\mathrm{P}}{2}\frac{1}{\omega_\mathrm{b}}\left(\mathrm{i^c}_{\mathrm{qs}}\,\varphi^{\mathrm{c}}_{\mathrm{ds}} - \mathrm{i^c}_{\mathrm{ds}}\,\varphi^{\mathrm{c}}_{\mathrm{qs}}\right) \tag{iii}$$

Where

$$\omega_b = \int \frac{p}{2\,J}\left(T_e - T_L\right) \tag{iv}$$

$$\varphi^{\mathrm{c}}_{\mathrm{qs}} = \mathrm{X_s}\,\mathrm{i^c}_{\mathrm{qs}} + \mathrm{X_m}\,\mathrm{i^c}_{\mathrm{qr}} \tag{v}$$

$$\varphi^{\mathrm{c}}_{\mathrm{ds}} = \mathrm{X_s}\,\mathrm{i^c}_{\mathrm{ds}} + \mathrm{X_m}\,\mathrm{i^c}_{\mathrm{dr}} \tag{vi}$$

The symbol/alphabet - P: denotes number of poles; J: moment of inertia (Kg/m2). The rotor d-q axis voltages $V_{dr}$ and $V_{qr}$ are set to zero as squirrel cage rotor is short circuited. $X_s$ is the self inductance of the coil, $X_m$ its corresponding mutual inductance with the other coil. The subscripts d, q, s, and r denote d-axis, q-axis, stator and rotor components respectively. Symbols Ψ and i denote the flux and current respectively. The superscript c denotes that the component belongs to an arbitrary frame, revolving at arbitrary speed. The symbol $\omega_b$ represents the base angular frequency in rad/sec.

## C. Diesel Engine (De) and Governor System

The diesel generator is composed of the diesel engine and Synchronous Generator of Wound rotor type [11, 18-19].

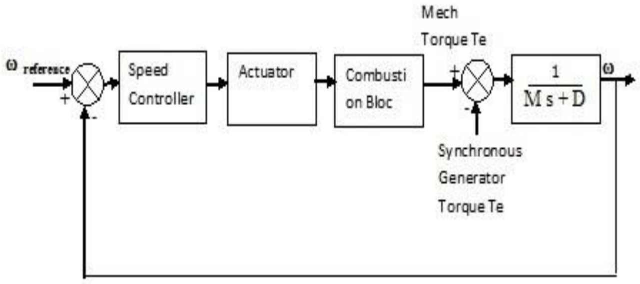

Figure-3 Block diagram of a diesel generator model

A diesel engine consists of a governor and an engine as shown in fig.3. The letters/symbols ‘M’, ‘D’, $\omega_{reference}$ denote the Inertia constant (in KW-sec/KVA), load-damping constant and angular speed (in rad/sec) respectively. The governor is a combination of speed regulator and an actuator. The DE speed control is isochronous, so the diesel speed governor will command the necessary fuelling rate to make the DE run at constant speed. The speed governor of the DG performs the task of frequency regulation by maintaining an instantaneous balance between the consumed and produced active power. In short, the DE behaves as a controlled source of active power, pumping the required power as and when needed. The governor and the connected diesel engine can be represented as a fourth order differential equation [17].

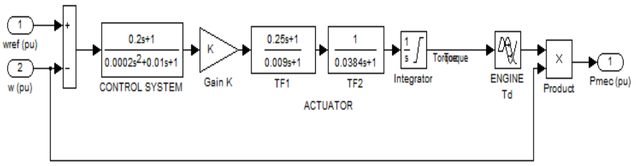

**Figure 4:** Governor and diesel engine, including actuator modeled in Simulink

The controller transfer function is given by

$$\mathrm{H_c} = \frac{\mathrm{k}(1+\mathrm{T_3\,s})}{(1+\mathrm{T_1 s}+\mathrm{T_1\,.T_2\,s^2})} \tag{vii}$$

The Actuator transfer function is given by

$$H_a = \frac{(1+T_4\,s)}{s\,(\,1+T_5\,.s)\,(1+T_6\,s)} \tag{viii}$$

Where k is regulator constant, $T_1$, $T_2$, $T_3$ are regulator time constant and $T_4$, $T_5$, $T_6$ are actuator time constants in seconds.

## D. Synchronous Machine

The detailed modeling and synchronous generator torque (Te) equations are given in the Simulink documentation. The Simulink model block for synchronous machine block is available in SimPowerSystems library of Simulink platform [11 – 16].

## E. Dump Loads

Dump loads are inserted to ensure frequency regulation during WO mode of operation of the system. They are basically resistive loads meant to dissipate excess power wasted as heat energy. The DL-control mechanism shown in fig.1 will introduce the required resistance from the resistance block needed for the power balance in the system. The excess power generated (with respect to the reference value) is integrated and fed to a sampling network and the digital signal, for introducing adequate units of resistance block, is generated. The required units of resistance or dump loads will gets introduced to the system for restoring the system frequency at its reference value.

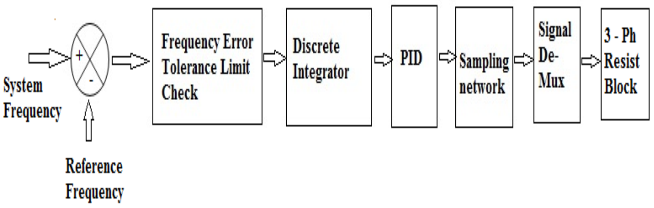

**Figure 5:** Control block diagram for introducing the required amount of DL to micro-grid

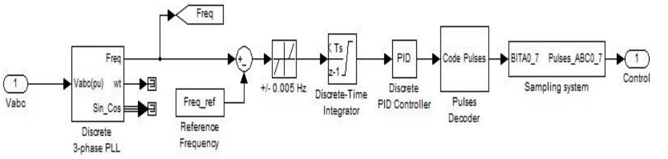

**Figure 6:** Realization of DL - Control block diagram in Matlab/Simulink

## Simulation Schematics

The Matlab-Simulink model of the WDHS is shown in Fig 7. The aim of the validation test carried out is to ensure that the system remains stable and meets system requirements especially during all transition periods. Step wind inputs are used as it is the worst case of transition and the real time transition will be smoother than step input.

The simulation starts at t=0, with low wind period, where the system is forced to work at DO mode.

At t= 2, the wind speed is increased by 4 m/s denoted by the step function and the system undergoes the first major transition from DO to WD mode.

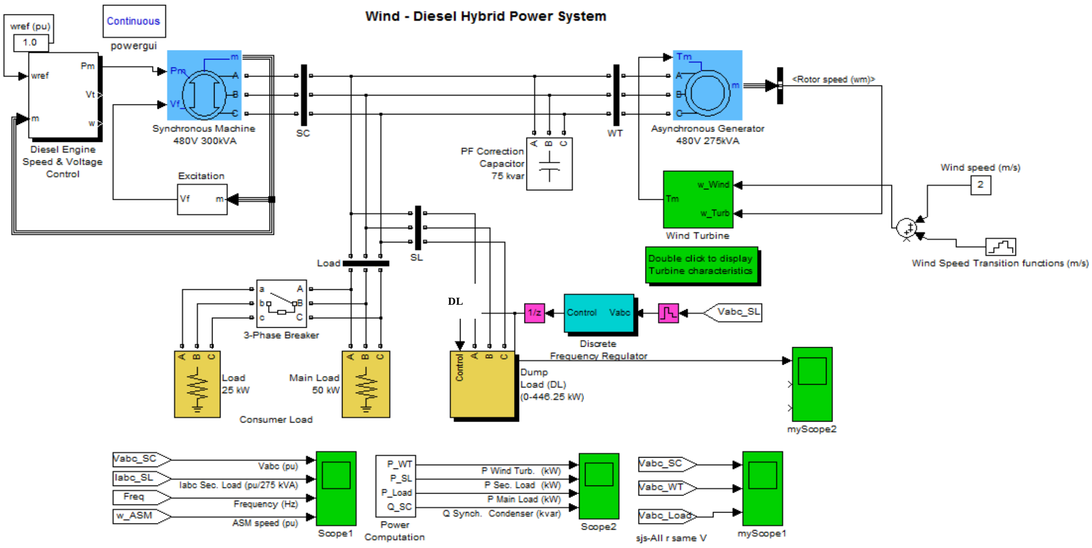

**Figure 7:** Simulink model of autonomous WDHS

The second major transition occurs at t=4, when the addition of step wind function is again increased by 4 m/s forcing the transition from WD to WO mode. It can be seen from the simulation graph, explained in following section that the active power from DG will be completely cut from the system and the excess power generated from

WG is dumped into the DL for regulating the system frequency and voltage. With further addition of wind at t=6, more DL are inserted into the system, thereby ensuring that frequency regulation in the system is properly maintained.

The reverse transition takes place at t=8, with the reduction in wind speed and the system will work stably in WD mode. At t=10, the wind is again reduced and the system comes to stable state for working in DO mode.

## Analysis of Simulation Results and Discussion

The variations of different parameters, when the system changes from DO mode to WD mode and finally reaches WO mode by the variation in wind speed, is shown. It can be seen that whenever a transition takes place from one mode to another, there will be transient overshoots in the corresponding parameters before settling into the steady state values.

During the working of system during very low wind ie in DO mode, the full active power was provided by the Diesel engine alone. After the transient interval the system was steady at 60 Hz and the speed of ASM was less than 1 pu.

When the mode was changed to WD mode at 2 sec, there was transient variation in all system parameters and the frequency was restored to reference frequency at steady state. It can be seen that the ASM speed becomes more than 1 pu, as it runs beyond its synchronous speed.

The mode has been changed to WO mode due to the step increase of wind at 4 sec. Similar to earlier change of mode; the transient parameter changes are visible in this case also.

Due to the sudden change to high wind state, the Grid frequency increases and the secondary load will be introduced in proportion to the wind to dissimilate/deviate the excess power generated beyond the capacity of the main load and thereby brings back the frequency to its steady state value.

## Conclusion

The paper describes the mathematical simulation model of Hybrid wind-diesel power system for analyzing the dynamic

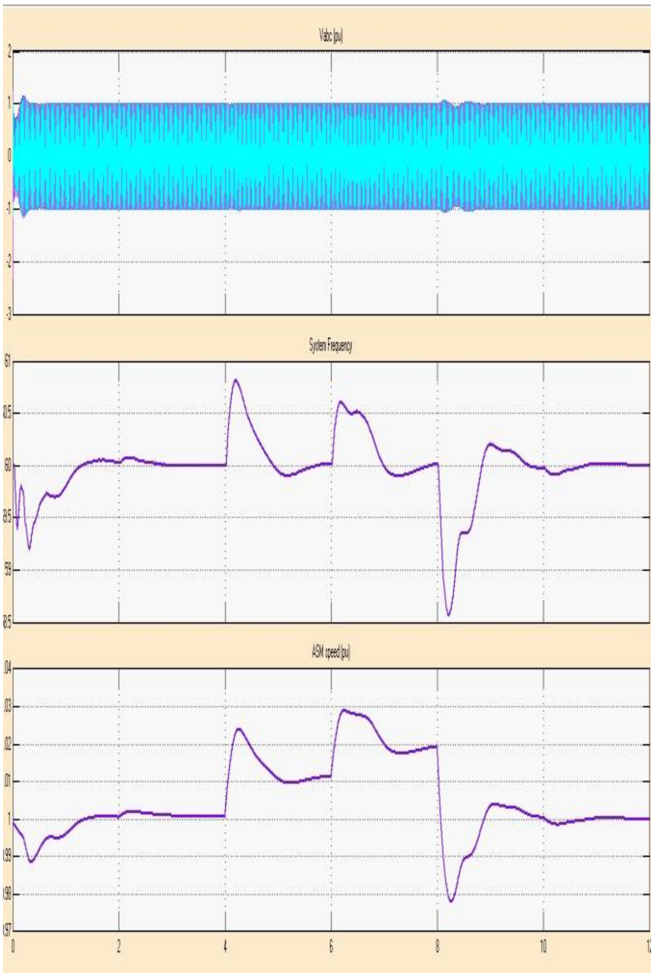

**Figure 8:** Plot of Grid Voltage (pu), Grid Frequency and ASM speed (pu) respectively at various modes of operation for various time instants

performance during the various modes of its operation and the developed model has been validated in Matlab/Simulink software. The system was tested in all possible transient stages of operations. Step functions were used for the creating the transient state, as it is the worst form of wind transients that can happen to the system. From the simulation results, it has been verified that the system can meets the power system stability conditions and hence can be used for power-critical applications like data centre loads. The system also meets high wind penetration level and the use of non-renewable fuel is reduced without compromising on the continuity of power. It is also evident from the simulation graphs that the power available from the system meets all the requirements of quality power including constant frequency and voltage magnitude.

The model has successfully simulated as a reliable model for the dynamic studies of hybrid wind-diesel system.

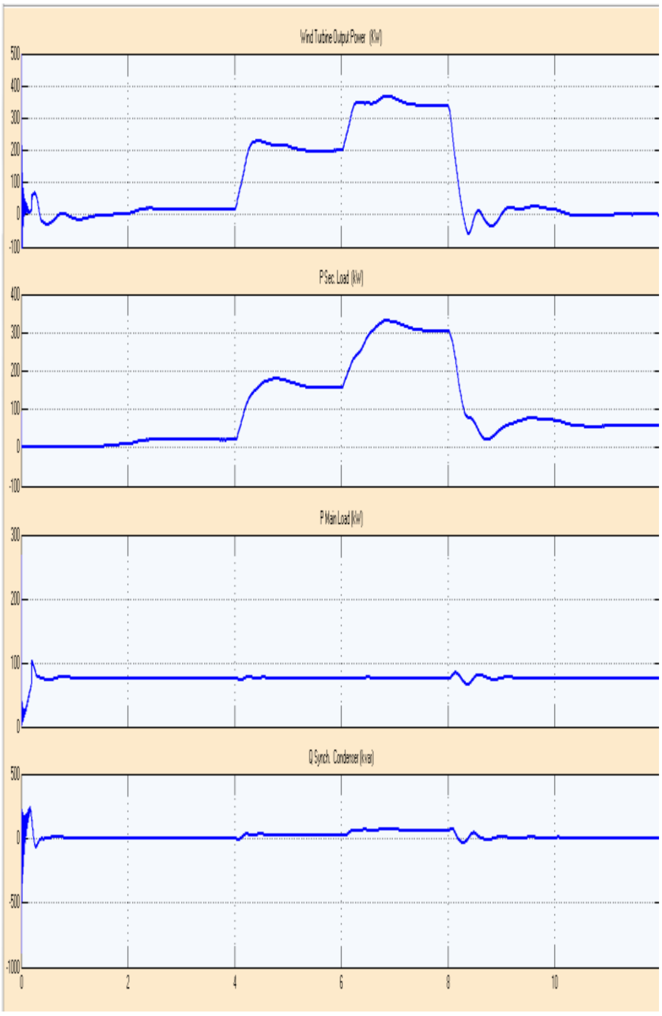

**Figure 9:** The plot of Wind Power (KW), Dump load (KW), Main load (KW) and condenser reactive power (KVAR) respectively for various time instants

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