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MODULAR SIMULATION OF A HYBRID POWER SYSTEM WITH DIESEL AND WIND TURBINE GENERATION

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ABSTRACT

In this paper, we present the modular simulation tool we developed to help study the system dynamics for wind-diesel power systems. The principal modules of the simulator, which include a diesel generator, a wind turbine generator, a rotary converter with a battery, a village load and a dump load, are described. With a case study, we demonstrate how the designer benefits from easily understanding the effects of system modifications. Using this tool, a designer can easily develop control strategies to balance the system power flows under different generation/load conditions.

INTRODUCTION

The advantage of hybrid power systems is the combination of the continuously available diesel power and locally available, pollution-free wind energy. With the hybrid power system, the annual diesel fuel consumption can be reduced and, at the same time, the level of pollution can be minimized. A proper control strategy has to be developed to take full advantage of the wind energy during the periods of time it is available and to minimize diesel fuel consumption. Therefore, a proper control system has to be designed, subject to the specific constraints for a particular application. It has to maintain power quality, measured by the quality of electrical performance, i.e., both the voltage and the frequency have to be properly controlled. This results in a need for a simulation study of each new system to confirm that a control strategy results in desired system performance.

Using the VisSim visual environment, we developed the modular simulation system to facilitate an application-specific and low-cost study of the system dynamics for wind-diesel hybrid power systems [1]. The simulation study can help in the development of control strategies to balance the system power flows under different generation/load conditions. Using the typical modules provided, it is easy to set-up a particular system configuration.

In this paper, we present the principal modules of the simulator and, using a case study of a hybrid system, we demonstrate some of the benefits that result from easily understanding the effects of the designer's modifications to these complex dynamic systems. In these systems, the voltage and the frequency are controlled by the diesel generator. The wind speed varies with time and so does the village load. Therefore, we regard the diesel generator as a controlled energy source, whereas the wind is an uncontrolled energy source and the village load is an uncontrolled energy sink. The difference between the power consumed by the village load and the power generated by the wind turbine is balanced by the diesel generator. On occasion, the wind speed can be very high [2], resulting in energy generation that exceeds the energy demand of the village load. Under such circumstances, the power from the diesel becomes very low and the wind may try to drive the diesel engine. Should the wind turbine override the diesel, the frequency control could be lost and the system would enter the instability region. To avoid this condition, the dump load is controlled so that the power generated by the diesel will always be higher than a minimum value. In addition, the energy surplus can be saved for future use by utilizing the rotary converter/battery assembly. Therefore, the dump load should be regarded as a controlled energy sink. When the battery is being discharged the rotary converter/battery assembly should be regarded as a controlled energy source. On the other hand, when the battery is being charged, it should be regarded as a controlled energy sink. By properly choosing the sequence of events programmed for our case study, we demonstrate that all operation aspects of the hybrid power system, briefly discussed above, can be easily taken into consideration. The single-line diagram of a simulated system, discussed as a case study, which involves all modules available in the simulator, is shown in Fig.1. We must include the point of common coupling (PCC) module as a node at which all power sources and power sinks are connected in every simulation diagram. The other principal modules shown in Fig.1 are the diesel generator (DG), the AC wind turbine (WT) with the induction generator and the wind speed time series as the input, the rotary converter (RC) with the battery bank (BB), the village load (VL) and the dump load (DL). In addition, R+jX represents the transmission line impedance. In all electrical simulations, we use the d-q axis convention and synchronous reference frame. In particular, in the PCC module, the q-axis and d-axis components v_{qs1} and v_{ds1} of the line voltage V_s are defined.

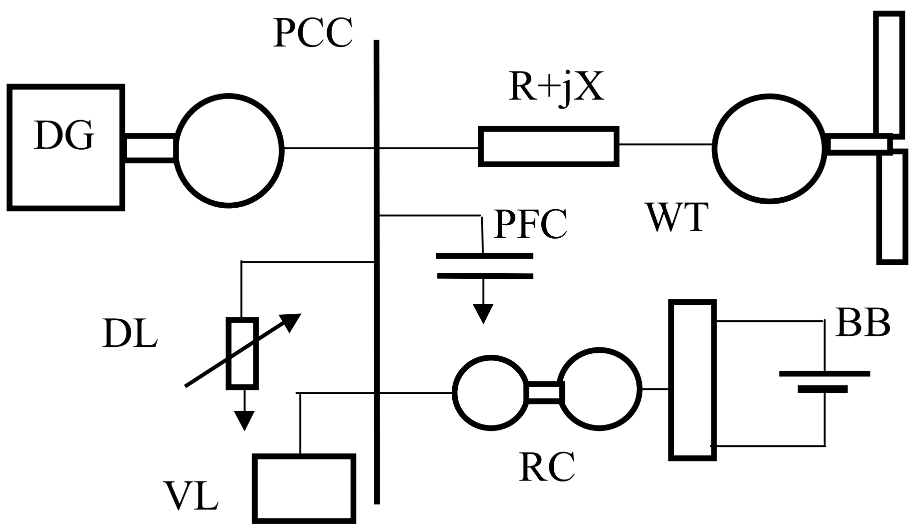

Fig.1 A typical hybrid power system

The electric machine models we used and modified in the development of the simulator can be found in many references [3, 4]. The wind turbine model can be derived from many papers in wind energy [5, 6].

BASIC CHARACTERISTICS OF THE PRINCIPAL MODULES OF THE SIMULATOR

Diesel Generator Module

The top-view block diagram of this module is presented in Fig.2. Notice that the user can easily set the voltage set point V_{s_ref} and the frequency (speed) set point f_{set} at required values. The frequency is controlled via the diesel torque and the line voltage is controlled through the field current of the synchronous generator. According to this block diagram, the speed control block generates a proper fuel/air ratio (represented by the variable $\%_{FUEL}$) for the diesel engine, so that the engine can generate the proper torque for the synchronous generator, as a result of which the power requirement can be satisfied and, simultaneously, the system frequency can be kept close to the required value. Notice also that the line voltage V_s is controlled by the voltage regulator through the proper adjustment of the field current of the synchronous generator.

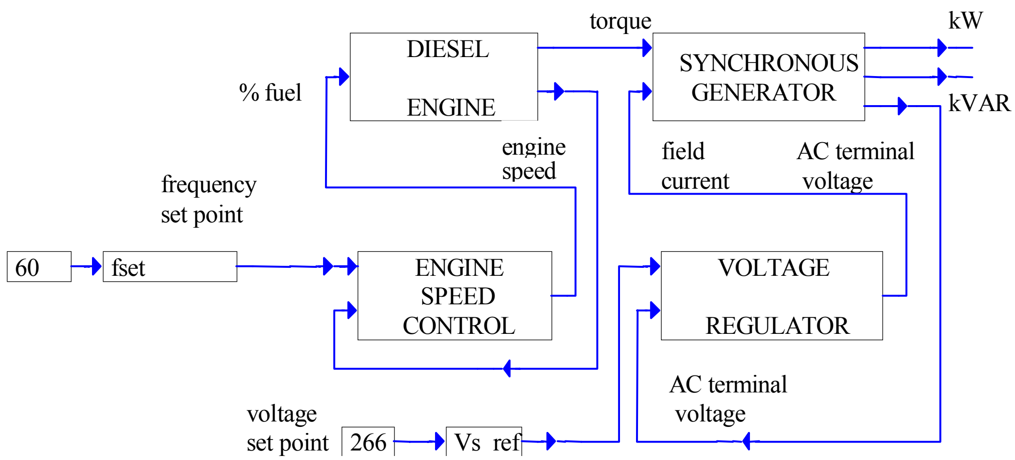

Fig.2 Block diagram of the diesel generator module: principal functional blocks and their interconnections

Figure 3 represents a simple simulation diagram of the diesel engine. Its $POWER=f(\%_{FUEL})$ characteristic is represented by the minimum value of the $\%_{FUEL}$ (the dead zone) and the slope of the straight line. The user defines this characteristic to approximate the diesel engine involved. One can see from Fig.3 that the rated power for the simulated diesel engine is 200 kW. Using the generated power and angular velocity $Gen_{m\_rad/sec}$, the torque T_{diesel} is generated assuming the first-order dynamics, whose time constant represents the diesel modeled. The actual power generated by the diesel, represented by the variable P_{gen}, is compared with the minimum diesel power (chosen in Fig.3 to be 25% of the diesel rated power or 50 kW in our simulation). The difference is used to control the number of active dump load elements (connected in parallel) needed to keep the generated power P_{gen} above the minimum diesel power. The number of active dump load elements is represented in this simulation diagram by the variable DL_{switch}. This variable is used to control the dump load.

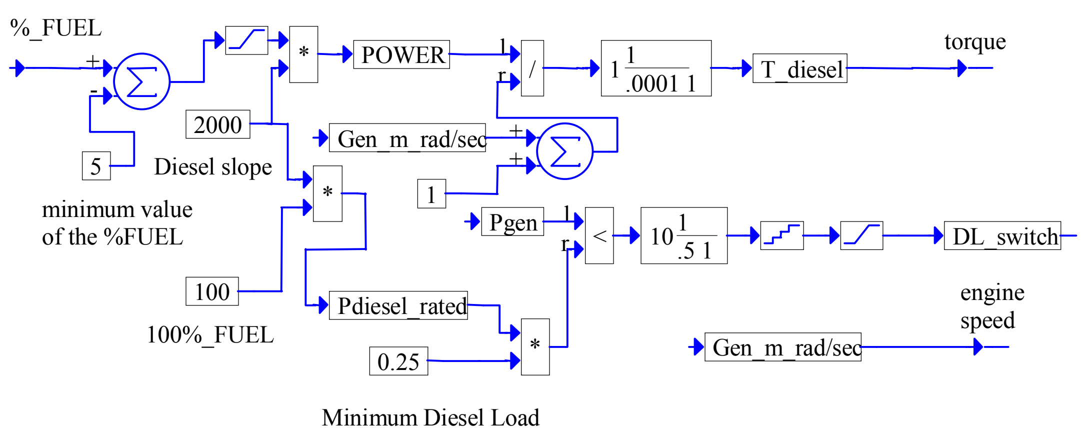

Fig.3 Simulation diagram of the diesel engine block

The torque equation

$$Gen_{m\_rad/\sec} = \frac{1}{J_{SD}} \int (T_{diesel} - T_{gen} - B_{SD} Gen_{m\_rad/\sec}) dt \,,$$

is simulated to obtain the angular velocity of the diesel generator $Gen_{m\_rad/sec}$. In this equation, the torque T_{gen} represents the generated electrical power P_{Egen_D} (includes generator power losses), i.e.,

$$T_{gen} = \frac{P_{Egen\_D}}{Gen_{m\_rad/\sec}} \quad ,$$

J_{SD} is the moment of inertia, and B_{SD} is the viscous friction coefficient of the synchronous generator.

The speed of the diesel engine is controlled by the variable $\%_{FUEL}$, generated by the governor (represented in the simulation by the PI controller), so that the relative frequency error 1- f/f_b is driven to zero, where the frequency f is determined by the relation $\omega = 2\pi f$. In this relation, the angular frequency ω is found as corresponding to the angular velocity $Gen_{m\_rad/sec}$.

The field current i_f of the synchronous generator is calculated according to the equation

$$i_f = \frac{1}{L_f} \int (V_f - R_f i_f) dt \,,$$

where V_f is the voltage applied to the field winding. It is controlled by the line voltage error $V_{s\_ref} - V_s$ through a PI controller.

AC Wind Turbine Module

Figure 4 represents the principal functional blocks of the AC wind turbine module with their interconnections and all inputs and outputs clearly shown and labeled. One also can see that the reactive power has two components: one contributed by the induction generator and the other one contributed by the power factor correction capacitors block. Clicking with the mouse on any of the blocks shown in Fig.4, the user obtains its lower level expansion. We briefly discuss below the principal components of this module, i.e., the induction machine and the wind turbine.

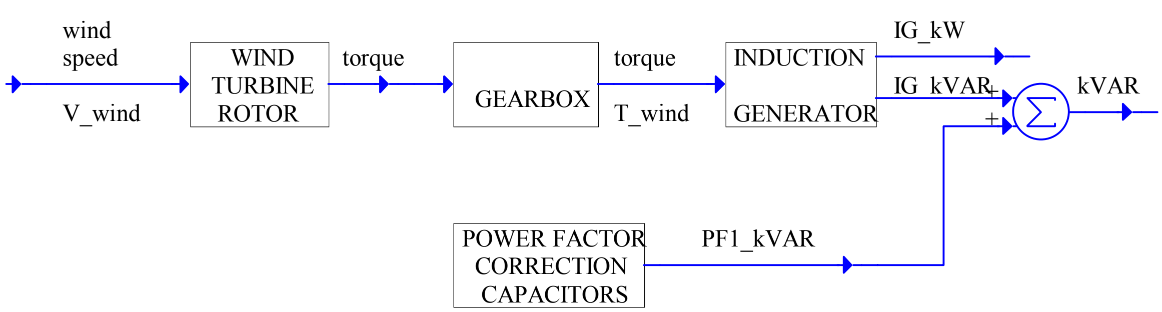

Fig.4 Block diagrams of the AC wind turbine module

Induction generator

The mechanical input to the induction machine comes from the wind turbine via the gearbox. It should be noted that there is neither voltage control nor speed control in this machine. At the beginning, when the wind speed increases above the cut-in speed, the induction machine operates as a motor, drawing a large starting current and absorbing the real power. As the motor speed comes closer to synchronous speed, the stator current decreases and eventually reaches the value of the rated current. As the rotor speed increases above synchronous speed, the induction motor becomes an induction generator and starts to generate power.

At the start-up of the induction machine there is an inrush current that must be sustained by the power system. The time during which the change of the rotor speed, from the value of zero to the rated speed, takes place is also influenced by the kinetic energy supplied to the wind turbine. The diesel generator must be able to provide the energy required by the induction generator and the wind turbine during the start-up operation without disturbing the power system stability.

Wind turbine model

The wind turbine is modeled based on the aerodynamic model provided by the wind turbine characteristic, described by the following equation defining the aerodynamic power P_{aero}, generated by the rotor:

$$P_{aero} = 0.5\rho A C_p V^3 ,$$

where V is the wind speed, C_p is the performance coefficient, A is the turbine rotor area swept and ρ is the air density. For a particular wind turbine C_p is given as a function of the tip-speed ratio TSR, defined as

$$TSR = \frac{\omega_r R}{V} ,$$

where ω_r is the angular speed of the rotor with the radius R. This function assumes a maximum for a certain value of TSR. From the wind speed input V and the rotor speed ω_r, the operating point of the wind turbine can be determined. When the induction machine is generating, which corresponds to its operation in the vicinity of synchronous speed, rotor speed is relatively constant.

Rotary Converter Module with the Battery

The block diagram of the rotary converter, shown in Fig.5, represents its principal functional blocks with their interconnections and all inputs and outputs clearly shown and labeled. As shown in this figure, the rotary converter simulation diagram consists of the following principal blocks:

- DC motor
- Synchronous generator
- DC machine field controller
- Voltage regulator.

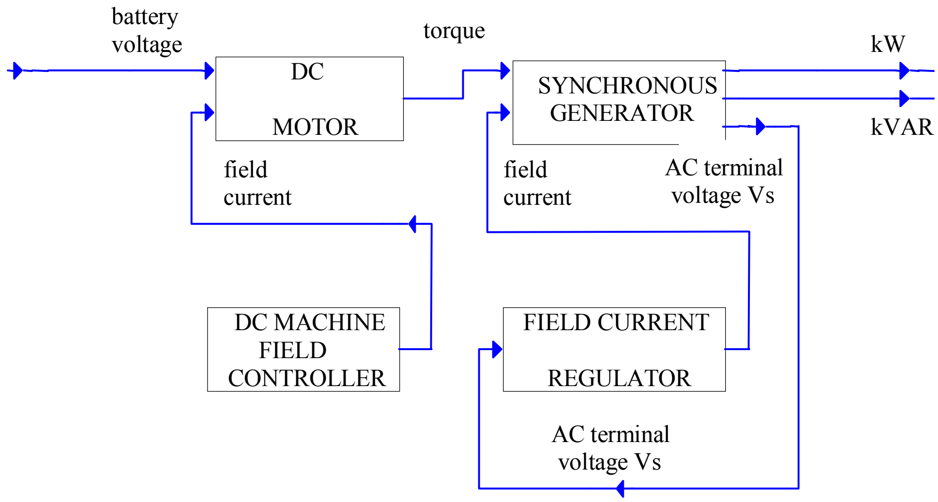

Fig.5 Block diagram of the rotary converter module.

The DC motor, when the battery is being discharged, generates a positive torque T_{DC}, driving the synchronous generator, and the DC power from the battery is converted into AC power supplied to the grid. Alternatively, when the battery is being charged, the DC motor works as a generator, i.e., it develops a negative torque T_{DC} or is driven by the synchronous generator which, due to this condition, is forced to operate as a synchronous motor. One of these two modes of operation is determined by the sign of the battery reference power P_{BAT_ref} with negative sign corresponding to charging the battery. In the simulation, the sign and the magnitude of P_{BAT_ref} can either be chosen by the user or can be used to help with the system energy balance.

We can control the DC machine by controlling the armature voltage/current or by controlling the field voltage/current. While the former mode of control requires a large-size power converter, the latter requires a smaller-size power converter. Thus, the latter mode of control is used in our application. The field current of the DC motor i_{f_DC} is generated so that the battery power

$$P_{BAT} = v_{BAT} I_{DC}$$

follows the battery reference power P_{BAT_ref}, where v_{BAT} is the battery voltage applied to the armature circuit of the motor and I_{DC} is the armature current.

The emf E_R, generated by the synchronous generator driven by the DC motor, has the phase angle

$$\gamma = \int (\omega_{RC} - \omega) dt$$

where ω_{RC} is the angular frequency generated by the rotary converter and ω is the angular frequency generated by the synchronous generator driven by the diesel engine. Note that the difference $\omega_{RC} - \omega$ is non-zero only in the transient and is used here to establish the angle γ which, in steady-state, remains constant as a result of the equality $\omega_{RC} = \omega$ forced by the diesel generator.

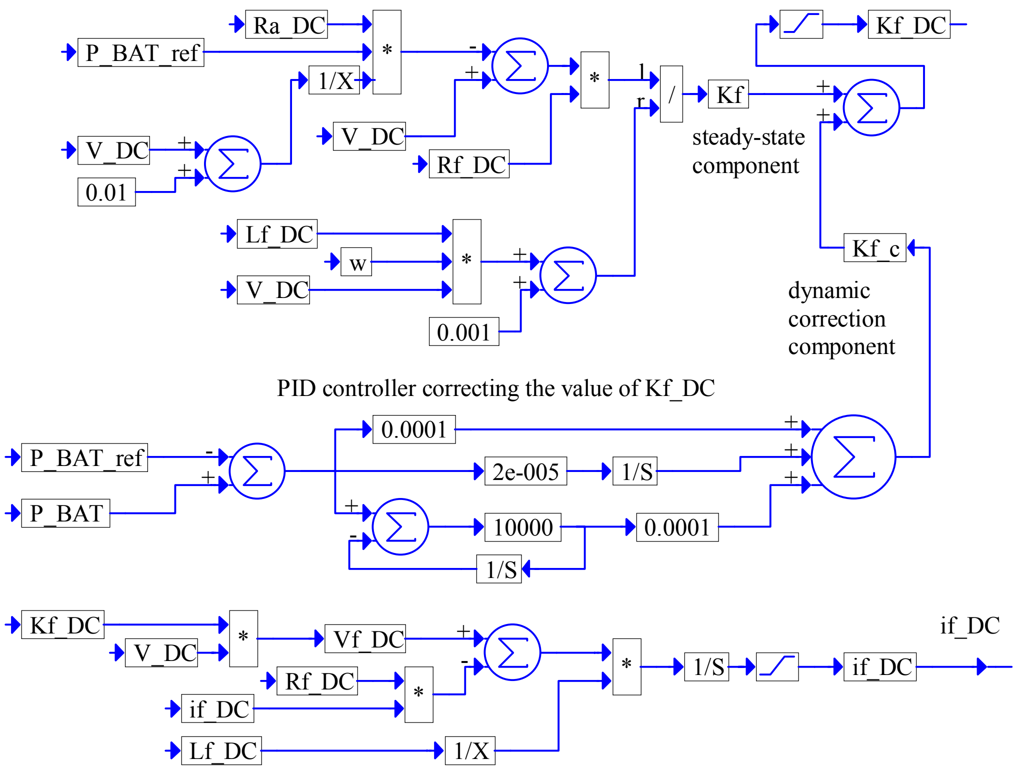

Fig.6 Simulation diagram of the DC machine field controller.

In Fig.6, the simulation diagram of the DC machine field controller is shown. It illustrates how the field current i_{f_DC} is generated to drive the error $P_{BAT\_ref} - P_{BAT}$ to zero. First of all, let us note that in this simulation diagram a new variable $V_{DC} \equiv v_{BAT}$ is used. The field current i_{f_DC} is controlled by the DC/DC conversion coefficient K_{f_DC} . In the upper part of Fig.6, this coefficient is shown as consisting of the steady-state component K_f and the dynamic or transient correction component K_{f_c}, i.e,

$$K_{f\_DC} = K_f + K_{f\_c} \ .$$

Let us reiterate that K_f represents the steady-state value of K_{f_DC}, obtained under two assumptions:

$$\omega_{RC} = \omega \quad \text{and} \quad P_{BAT} = P_{BAT\_ref} \ .$$

Therefore, the necessary dynamic correction component K_{f_c} *is* generated as the output of the PID controller whose input is the difference $P_{BAT} - P_{BAT\_ref}$. Due to the PID action, he coefficient K_{f_c} will, at the beginning of the transient, be greater than 1. Therefore, in order to make sure that K_{f_DC} remains between 0 and 1, the sum $K_f + K_{f\_c}$ is passed through the limiter (as shown in Fig.6).

Dump Load Module

The dump load is a set of parallel load resistances. Each parallel resistance can be turned on or off upon command. In a real application, the dump load may take the form of an electric heater to heat air or water. The main purpose of the dump load is to keep the diesel-generated power above a user-prescribed fraction of its rated power. It is introduced to avoid overpowering the diesel by the wind turbine but, under special circumstances, it also can be used to control the frequency. Any of these two control strategies dynamically determines the number of the dump load elements to be connected in parallel. For diesel power control, this number is represented by the variable *DLswitch*, determined in the simulation diagram in Fig.3. For the frequency control strategy, the calculation of this number is directly performed in the dump load module, which also contains a user-operated switch for choosing a particular strategy.

A SIMULATION CASE STUDY OF THE DYNAMICS OF A HYBRID POWER SYSTEM

The power system we chose to simulate consists of the following principal modules:

- Diesel generator with rated power of 200 kW and minimum load of 50 kW
- AC wind turbine driven by the wind given by a file of the wind speed time series
- Village load of 50 kW at the power factor pf=0.75, switched to 80 kW at t=11s
- Rotary converter with a preprogrammed battery reference power
- Dump load with the diesel power control strategy selected.

The results of the simulation are shown in Fig.7. We use the convention that the power generated is positive and the power consumed is negative. Notice that at t=0 the diesel generator starts up. At approximately t=4s, the line voltage V_s reaches its reference value of 266V, the relative frequency f/f_b is close to 1, and both the real diesel power generated and the village power consumed are approximately 50 kW, as required. The first action of the diesel power control strategy appears in the transient period (before this steady state is reached) is seen as an additional load on the diesel when its generated power is below 50 kW.

At t=5s, the battery reference power of the rotary converter is switched from the level of 0 to the level of 20 kW. We note that the response represented by the power P_{bat} is slow. This is a consequence of the field current control of the DC machine in the rotary converter. This additional power generation is immediately followed by its consumption by an increasing dump load, so that the diesel generation does not drop below the minimum value of 50 kW. This load is taken off immediately when at t=7.5s the induction machine starts to motor the wind turbine. In this phase of the simulation, the power is provided by both the diesel generator and the rotary converter.

At t=10s, the power consumption of the induction machine, reaching synchronism, rapidly drops and eventually, at t=11s, it starts to generate. The power released and then generated by the AC wind turbine is now consumed by the village load, increased at t=11s to the value of 80 kW, and by the rotary converter, which at t=12s starts to charge the battery due to the preprogrammed drop of the battery reference power from the value of 20 kW to the value of –10 kW. One can also notice small corrections of the power consumed, performed in this phase of the simulation by the diesel power control strategy. The influence of the sudden changes in the power generated and consumed in the system can be noticed in the line voltage V_s and the relative frequency f/f_b transients, but their quality remains satisfactory.

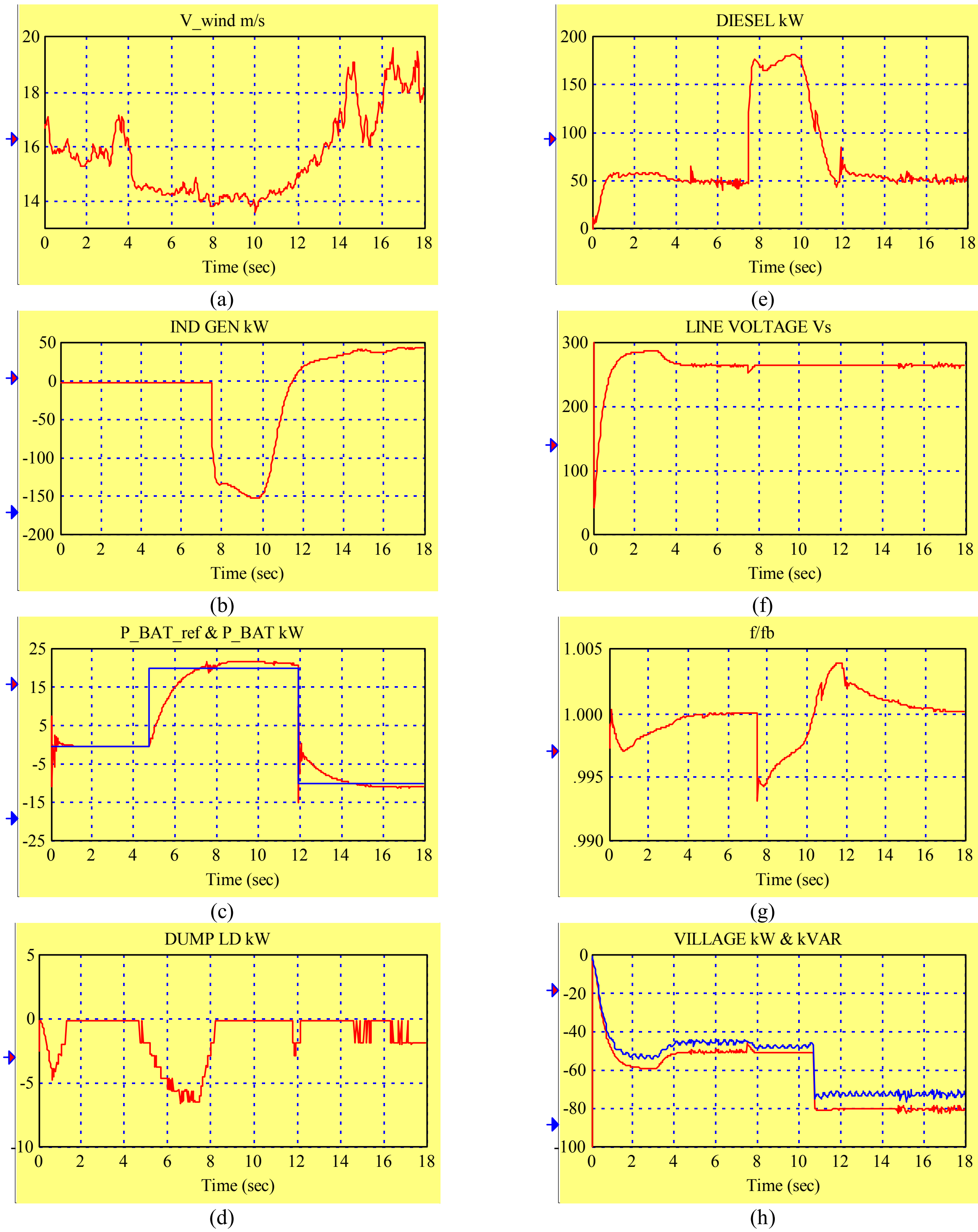

Fig.7 Traces of wind speed, power, voltage and frequency for various components

CONCLUSION

The simulation results of a hybrid power system with diesel and wind power generation, presented in this paper, demonstrate that the modular simulation system, developed using the visual programming environment, constitutes a very useful tool for analysis and design of such systems.

The modular simulation system has been developed to

- Facilitate an application-specific and low-cost performance study of wind-diesel hybrid power systems (both mechanical and electrical components are simulated)
- Analyze both static and dynamic performance
- Help in the development of control strategies
- Simulate different wind speed profiles and different village load profiles.

The system has the following capabilities/characteristics:

- Modular and multilevel structure provided by VisSim visual environment
- Clear and easy-to-understand system presentation
- Setting-up a particular desired configuration is within a click of the mouse
- Modifications are easy to make
- Effects of system modifications can be immediately examined.

ACKNOWLEDGMENTS

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