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Modelling and simulation of a high penetration wind diesel system with battery energy storage

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ABSTRACT

Wind Diesel Hybrid Systems (WDHS) are isolated power systems which combine Diesel Generators (DG) with Wind Turbine Generators (WTG). Depending on the generators which are supplying, high penetration (HP) WDHS have three operation modes: Diesel Only (DO), Wind Diesel (WD) and Wind Only (WO). The HP-WDHS presented in this article consists of a Diesel Engine (DE), a Synchronous Machine (SM), a Wind Turbine Generator, the consumer load, a Ni-Cd Battery based Energy Storage System (BESS) and a Dump Load. The DE can be engaged (DO and WD modes) or disengaged (WO mode) from the SM by means of a clutch. All the models of the previously mentioned components are presented and the performance of the WDHS has been tested through dynamic simulation. Simulation results with graphs for the frequency and voltage of the isolated power system, active powers generated/absorbed by the different elements and the battery voltage/current/state of charge are presented for a load change in WO mode and for the transition from WO to WD mode in order to substitute a supplying BESS for the DE as the active power source.

1. Introduction

A Wind Diesel Hybrid System (WDHS) is any autonomous electricity generating system using Wind Turbine Generators(s) (WTG) with Diesel Generator(s) (DG) to obtain a maximum contribution by the intermittent wind resource to the total produced power, while providing continuous high quality electric power [1]. The main goal with these systems is to reduce fuel consumption and in this way to reduce system operating costs and environmental impact. If the WDHS is capable of shutting down the Diesel Generators during periods of high wind availability, the WDHS is classified as high wind penetration. High penetration (HP) WDHS have three operation modes: Diesel Only (DO), Wind Diesel (WD) and Wind Only (WO) [2]. In DO mode the Diesel Generators supply the active and reactive power demanded by the consumer load (WTGs are disconnected). In WD mode, in addition to DG(s), WTG(s) also supply active power. In WO mode the Diesel Generators are not running, only the wind turbines are supplying active power, so that no fuel is consumed in this mode.

Several papers have been published on the subject of WDHS dynamic simulation. In [3] the interaction between one DG and a constant/variable speed WTG is studied. In [4] a no-storage WDHS is simulated against several perturbations, among them the connection of a WTG to the DG isolated grid (DO to WD transition). In a previous work [5] a HP-WDHS with a BESS is simulated in WO mode, but the battery is modelled by a simple constant voltage source. In [6] the modelled HP-WDHS has a DG with a locked-disengaged simplified clutch model and it is simulated the mandatory transition from WO to WD when the active power generated is less than consumed. During this type of WO to WD transition the power system is without control until the DE is added to the system.

In the present article the WO mode is also simulated, but a more elaborated model for a Ni-Cd battery is used and the main battery variables: current, voltage and state of charge are presented during the simulation. Additionally, in the present article a more realistic clutch model is also used to transition from WO to WD, but in this case the transition simulated is controlled and it is done in order to substitute a supplying BESS by the DE.

After this introductory Section 1, this article is organized as follows: Section 2 presents the HP-WDHS architecture discussed in this article along with its control requirements, Section 3 presents the control system that has been used, Section 4 shows the modelling of the WDHS components, Section 5 presents the WDHS response in WO mode against a load step and the controlled WO to WD transition simulation and Section 6 emphasizes the effectiveness of using the Ni-Cd BESS.

2. The isolated power system (WDHS architecture)

The high penetration WDHS of Fig. 1 comprises one DG and one WTG. The DG consists of a Diesel Engine (DE), a Synchronous

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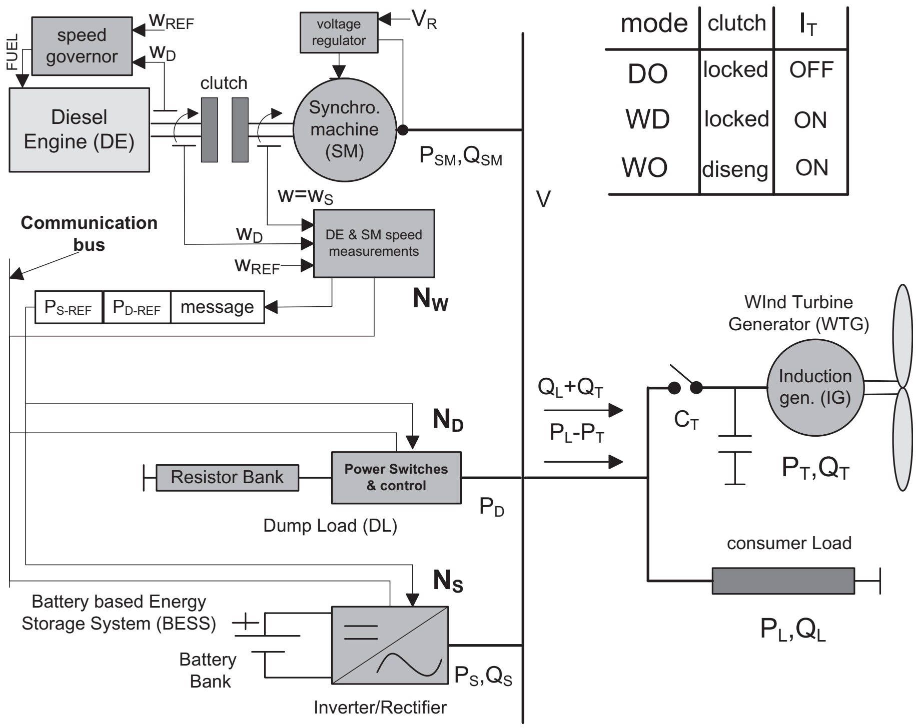

Fig. 1. Layout of the isolated high penetration WDHS and DCS.

Machine (SM), and a friction clutch. The SM generates the voltage waveform of the isolated grid and its automatic voltage regulator controls the system voltage to be within the prescribed levels during the three modes of operation. For this reason the SM must be always running close to its rated speed. The DE provides mechanical power to the SM and its speed governor (speed regulator + actuator) controls the DE speed. In this article 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 DE is needed to supply active power and regulate the system frequency in the DO and WD modes. The clutch has three states: engaged, locked and disengaged [7]. If the clutch is disengaged, the frictional surfaces are not in contact and no torque is transferred from the DE to the SM, so that if C_T is closed the operation mode is WO. In WO mode since the DE and SM axes are independent, the DE must not be running in order to save fuel, but in this paper it will run at slow speed as it is explained later on. With the clutch engaged, the frictional surfaces slip past one another and kinetic friction torque is transferred to the SM. Finally, if the clutch is locked, the frictional surfaces are locked together without slipping and static friction torque is transferred to the SM. With the clutch locked the DE and SM turn at the same speed ($\omega = \omega_D$ in Fig. 1) and the WDHS is in the DO/WD mode if the WTG circuit breaker C_T is opened/closed respectively. Several real HP-WDHS include a clutch to transition from WO to WD modes and vice versa [8,9].

The WTG consists of a Wind Turbine (WT) driving an Induction Generator (IG) directly connected to the autonomous grid conforming a constant speed stall-controlled WTG (no pitch control). The WTG produced active power P_T depends among other factors on the cube of the wind speed [2] and since the WT used has no pitch control, there is no way to control the WTG active power, so it behaves as an uncontrolled source of active power. The IG consumes reactive power so a capacitor bank has been added to compensate the power factor.

The Dump Load (DL) consists of a set of semiconductor power switches and a binary bank of resistors. By closing/opening these power switches, the DL consumed active power can be controlled behaving as a controlled sink of active power. The Battery based Energy Storage System (BESS) consists of a battery bank and a power converter that interfaces the battery bank to the autonomous grid. The BESS can store or retrieve power as needed, so it behaves as a controlled sink/source of active power.

The system frequency is regulated by maintaining an instantaneous balance of the active power consumed and produced. In DO and WD modes the DE speed governor modulates the DE active power in order to accomplish this balance, so the DE behaves as a controlled source of active power. In WO mode the clutch is disengaged and the active power consumed by the load (P_L) is produced only by the WTG (P_T). Since P_T (also called wind power) and P_L are uncontrolled the DL + BESS must perform the instantaneous balance of the active power. Being P_D the power consumed by the DL, P_S the power consumed/supplied by the BESS, J the SM inertia and ω the SM shaft speed, the power equation of the SM in WO mode if no losses are taking into account is:

$$P_T - P_L - P_D - P_S = J\omega \frac{d\omega}{dt} \quad (1)$$

$$\frac{d\omega}{dt} = 0 \Rightarrow P_T - P_L = P_D + P_S \quad (2)$$

where P_T is considered positive if produced and P_L, P_D and P_S are considered positive if consumed. In Eq. (1) the SM shaft speed ω is in rad/s ant it is related with the system frequency (frequency of the voltage waveform) f by $\omega = 2\pi f/p$, with p the number of pole pairs of SM. Eq. (2) shows that to obtain a synchronous shaft speed constant ($d\omega/dt = 0$), the DL + BESS combination must consume power when P_T exceeds P_L and the BESS must generate power when P_T is less than P_L. The situation where the BESS supplies power is temporary, so that if this situation persists the control system of the WDHS must order to start the DE and when the speed difference between DE and SM is small enough engaged the clutch, changing to the WD mode. With the clutch locked the DE will supply the necessary active power P_{DE} to keep the system frequency at rated value.