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# STUDY AND ANALYSIS OF WIND-DIESEL HYBRID SYSTEM BY SIMULINK

Kishor Bhimrao Gawale[1]
[1]Department of Electrical Engineering, Veermata Jijabai Technological Institute, Mumbai, India.

**Abstract—** Wind Diesel Hybrid Systems (WDHS) are isolated power systems which combination of Diesel Generators (DG) with Wind Turbine Generators (WTG). Depending on the generators which are supplying high penetration (HP) WDHS have three operation modes 1) Diesel only DO 2) Wind Diesel WD & 3) Wind only WO.The DE can be engaged (DO & WD modes)or disengaged (WO mode) From the SM by means of a clutch. The WDHS presented in this paper consists of a Diesel Engine DE, Synchronous Machine (SM) a Wind Turbine Generator the consumer load , a Ni-Cd Battery based energy Storage System(BESS) and a Dump Load. Simulation results with graphs for the frequency and voltage of the isolated power system, active powers generated by the different elements and the battery voltage , current , state of charge are presented for a load charge 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.

**Index Terms—**Battery based Energy Storage Systems (BESS), Diesel Only (DO), Distributed control systems(DCS), Dynamic Simulation (DS), Isolated power systems , Wind Diesel (WD), Wind Only (WO)

## I. INTRODUCTION

A Wind Diesel Hybrid System (WDHS) is any autonomous electricity generating system using Diesel Generator (DG) with Wind Turbine Generators (WTG) to obtain a maximum contribution by the intermittent wind resource to the total produced power, while providing continous high quality electric power. In WD mode, in addition to DG, WTG also supply active power. In WO mode the Disel Generators are not running, only the wind turbines are supplying active power, so that no fuel is consumed in this mode. The main goal with these systems is to reduce fuel consumption and in this way to reduce system operating costs and environmental impact. In 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.

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. In the WO mode is also simulated, but a more elaborated model for a Ni-Cd battery is used and the main battery variables- voltage, current and state of charge are presented during the simulation.

## II. WDHS ARCHITECTURE

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

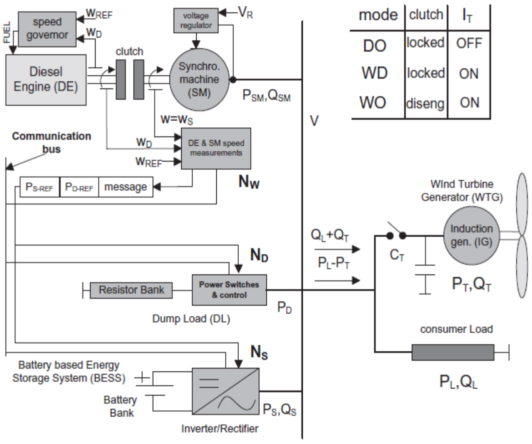


*Fig 1.Layout of the isolated high penetration WDHS and DCS*

The DE provides mechanical power to the SM and its speed governer controls the DE speed. The SM generates the voltage waveforms 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. The clutch has three states (i) engaged (ii) locked (iii) disengaged If clutch is disengaged the frictional surfaces are not in contact and no torque is transferred from the DE to the SM, so that if CT 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. 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 and the WDHS is in the DO/WD mode if the WTG circuit breaker CT is opened/closed respectively.

The Dump Load (DL) consists of a set of semiconductor power switches and a binary bank of resistors. 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. In DO and WD modes the DE speed governer modulates the DE active power in order to accomplish this balance, so the DE behave as a controlled 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 ώ the SM shaft speed, the power equation of the SM in WO mode if no losses are taking into account is:

$$P_T - P_L - P_D - P_S = J\,\omega(d\,\omega/dt) \qquad [1]$$

$$[d\,\omega/dt]=0 \;\rightarrow\; P_T - P_L = P_D + P_S \qquad [2]$$

## III. CONTROL SYSTEM

The DL and BESS in the presented power system is by means of a Distributed Control System (DCS). A DCS comprises several CPU based electronic control units physically distributed and linked by a communication network. As it can be seen in Fig. 1, the presented DCS consists of three nodes: a SM and DE shaft speeds measurement sensor node $N_W$ and two actuators nodes: the DL converter $N_D$ and the BESS converter NS. The type of control that the sensor node $N_W$ applies depends on the operation mode. As commented in the previous section, in WD modeN the DE performs the isochronous speed control, so $N_W$ calculates a PD frequency regulator whose input is the frequency error (difference between the current frequency and the power system nominal frequency 50/60 Hz) and whose output is the reference power $P_{REF}$ needed to be absorbed ($P_{REF} > 0$) by the DL + BESS combination or to be supplied ($P_{REF} < 0$) by the BESS to balance the active power of the system. In WO mode, there is no DE controlling the system frequency, so to calculate $P_{REF}$, the sensor node $N_W$ applies a PID regulator to the frequency error to control the power system frequency. The integral part of the PID eliminates the steady state frequency error, performing an isochronous speed control.

The node NW also calculates the power sharing between DL and BESS when $P_{REF} > 0$ by computing the reference power to be dumped by DL $P_{D\text{-}REF}$ and the reference power to be stored/retrieved$P_{S\text{-}REF}$ by BESS, so that :

$$P_{REF} = P_{S\_REF} + P_{D\_REF} \quad [3]$$

$$0 \leq P_{D\text{-}REF} \leq P_{D\_NOM}, \quad |P_{S\_REF}| \leq P_{S\text{-}NOM} \quad [4]$$

(3) is simplified to $P_{REF} = P_{D\text{-}REF}$ if battery is fully charged/failure and (4) means that the DL can only consume power up to its rated power ($P_{D\text{-}NOM}$) and BESS can consume/supply power up to its rated power ($P_{S\text{-}NOM}$). On the other hand, the nodes of a DCS exchange information between them through message passing. In order to coordinate DL and BESS actuators when $P_{REF} > 0$, the sensor node $N_W$ shall communicate with the message shown in Fig. 1 the current reference powers $P_{S\text{-}REF}$ and $P_{D\text{-}REF}$ through the network to the actuator nodes $N_D$ and $N_S$. This message is periodic and guarantees that both actuators receive its reference power at the same time.

## IV. SIMULATION SCHEMATICS

The Matlab-Simulink model of the WDHS of Fig. 1 is shown in Fig. 2. Some of the components described next such as the IG, the SM and its voltage regulator, the consumer load, etc. are blocks which belong to the Sim Power Systems library for Simulink. The SM has a rated power ($P_{SM\text{-}NOM}$) of 300 kVA. An IEEE type 1 Voltage regulator plus an exciter regulates the voltage in the SM terminals. The mechanical parts of the DE and the SM and the friction clutch are modelled by using blocks of the SimDriveLine library. The model inside the corresponding block of Fig. 2 includes the inertia constants of the SM ($H_{SM}$ = 1s) and DE ($H_{DE}$ = 0.75 s) and the friction clutch. The DE mechanical torque $T_D$ and the SM electric torque $T_S$ both in per unit values (pu) are the inputs of the block. The shaft speeds of the DE $\omega_D$ and SM $\omega_S$, both in pu, are the outputs of the block.

The clutch state is set by the binary input signal CLUTCH, which controls the clutch pressure actuator. When CLUTCH signal is high (clutch engaged/locked), the pressure actuator is ordered to apply force normal to the surfaces. When CLUTCH signal is low (clutch disengaged), the pressure actuator is ordered to relieve the force normal to the surfaces. The actuator dynamics is modelled as a simple first order system with 0.04 s time constant whose input is CLUTCH and whose output is the normalized clutch pressure. The mechanical parts and Friction Clutch Block in Fig. 2

The DE along with its actuator and speed regulator are included in the Diesel Engine block of Fig. 2. This block has the current DE speed (pu) as input and outputs the mechanical torque (pu) to take the DE speed to its speed reference. The DE has been simulated by means of a gain, relating fuelling rate to torque (lower/upper torque limits are 0/1.1 pu) and a dead time. The actuator has been simulated by a second order system and the speed regulator by a PID control.

The constant speed stall-controlled WTG consists of an Induction Generator (IG) of 275 kW (WTG rated power $P_{TNOM}$ = 275 kW) directly connected to the autonomous grid and the Wind Turbine (WT) block. This WT block contains the wind turbine characteristic which defines the mechanical torque applied to the IG as a function of the wind speed and the IG shaft speed. This WTG has no pitch control, so there is no way to control the power it produces. The dump load consists of eight three phase resistors connected in series with GTO switches. The resistors values follow an 8 bit binary progression so that the power consumed by the DL, provided that the voltage in the isolated grid is nominal, can be expressed in the form:

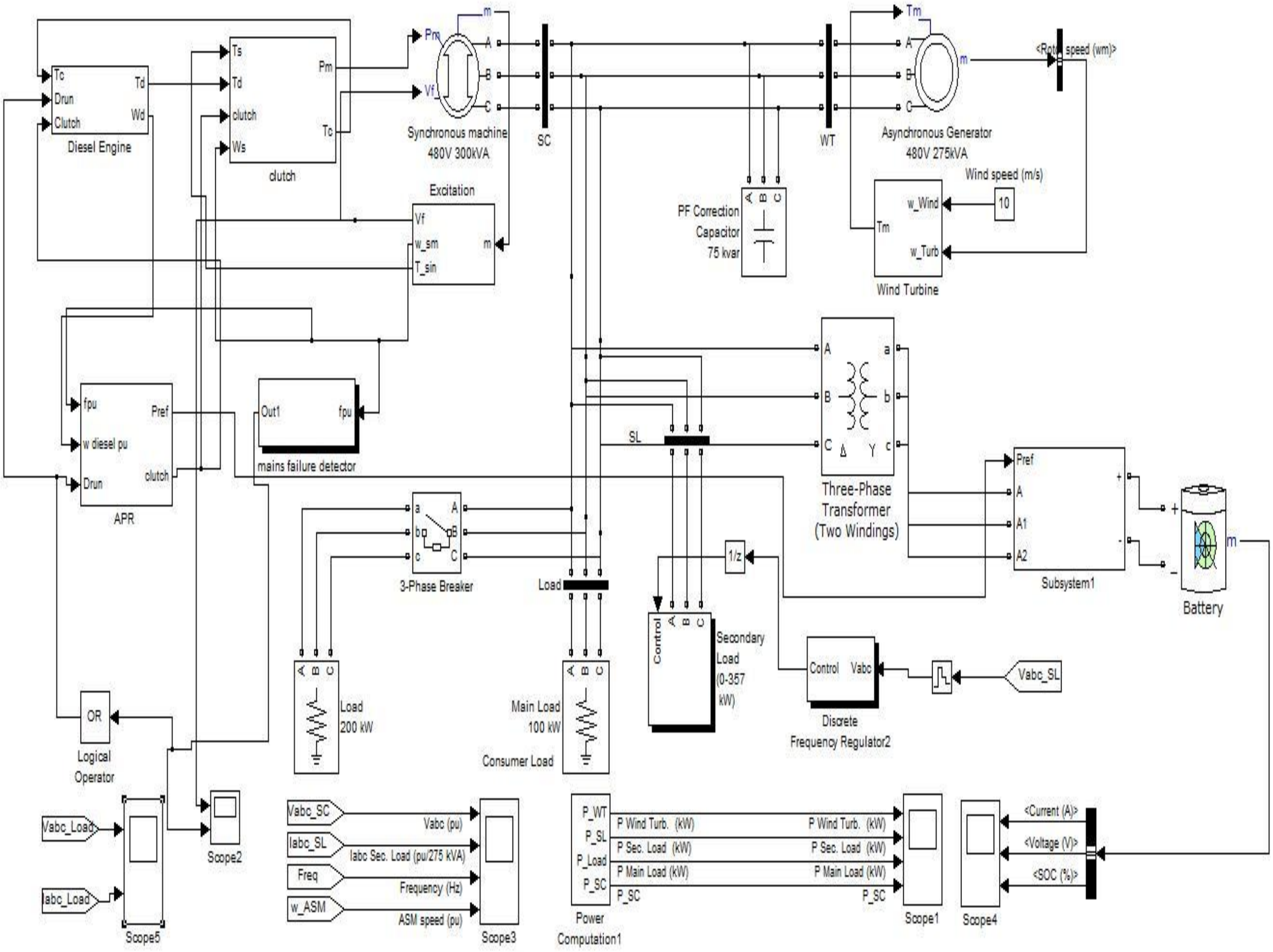


*Fig. 2. Simulink schematic of WDHS and DCS*

$(I_0 + I_1 2^1 + \ldots + I_7 2^7)P_{STEP} = X_{D\_REF} P_{STEP}$ [5]

(5) means that the power can be varied discretely from 0 to 255.$P_{STEP}$, where $P_{STEP}$ is the power corresponding to the least significant bit and $I_J$ is ‘‘1’’ when the associated GTO is turned on and ‘‘0’’ when the GTO is turned off. For this article $P_{STEP}$ = 1.4 Kw and then $P_{D\text{-}NOM}$ = 357 kW, which is a 30% greater than $P_{T\text{-}NOM}$, so that the WDHS can be controlled in WO mode even in the case of no consumer load and BESS fully charged/failure. The BESS is based on a Ni-Cd battery bank, a LC filter, an IGBT three-phase bidirectional Current Controlled Inverter (CCI) of rated power $P_{S\text{-}MOM}$ = 150 kW and a 150 kVA elevating transformer.

The elevating transformer isolates the three phase power inverter and the battery bank from the autonomous grid. Its rated line to line voltage in the grid/inverter sides are 480/120 VAC. The 240 V Ni-Cd battery model consists of a DC voltage source function of the state of charge (SOC), based on the discharge characteristic of the battery, and an internal resistance of assumed constant value. The energy stored in the battery is 93.75 kWh, which is obtained from a storage energy need of 15 min for the 150 kWCCI rated power and a Ni-Cd battery operating between 35% and 75% of its rated capacity

(150 kW_15 min/(0.4_60 min/h) = 93.75 kWh). This 93.75 kWh corresponds to a capacity C of 390.625 Ah (93.75 kWh/240 V = 390.625 Ah). The Ni-Cd battery is tolerant to a current ripple of rms value up to 0.2 C with the only effect of an increased water usage. Connecting the battery directly to the DC side of the power converter would excess this ripple size, so a LC filter has been used for smoothing the battery current.

The described short term BESS helps to cover the load during short term load peaks or wind power deficits, minimising the number of the DG start/stop cycles needed. This start/stop cycles minimization reduces the fuel consumption and DG wearing and the sizing made in is done according to these benefits. Also short term BESS improves the frequency stability and the continuity of supply of the isolated power system as it is shown in the simulation section. In addition to previous mentioned benefits, long term energy storage allows to match a variable and uncontrolled renewable energy production to a generally variable and hardly predictable load demand. Long term storage allows storing excess renewable energy to meet the load during days of higher than average load or lower than average renewable energy availability. In the sizing of long term energy storage in order to obtain the most cost efficiency configuration in an isolated power system is addressed.

The WD/WO_ block of Fig. 2 sets the operation mode selected by the WDHS DCS. Its output is ‘‘1’’ for WD mode and ‘‘0’’ for mWO mode. If WD/WO_ = 1 or CLUTCH = 1 the speed reference to the DE is 1 pu as the DE is needed to keep the system frequency at rated value. In WO mode (WD/WO_ = 0 and CLUTCH = 0) the DE speed reference is 0.3 pu, so that the DE is kept running instead of being stopped to simplify the simulation of the DE cranking system. When a DE is started the cranking system is switched on until the DE reaches the firing speed, where the DE internal combustion process starts, and then, the DE cranking system is switched off and the DE speed controller is activated with a speed reference of 1 pu. For this article the time the cranking system is switched on is supposed to be 0.5 s, and the firing speed is 0.3 pu, which are standard values for a DE. So if the WDHS is in WO mode and the WD/WO_ changes from 0 to 1, the diesel speed reference is not changed to 1 pu until the 0.5 s delay of Fig. 2 elapses, to take into account that the DE is already running at 0.3 pu firing speed.

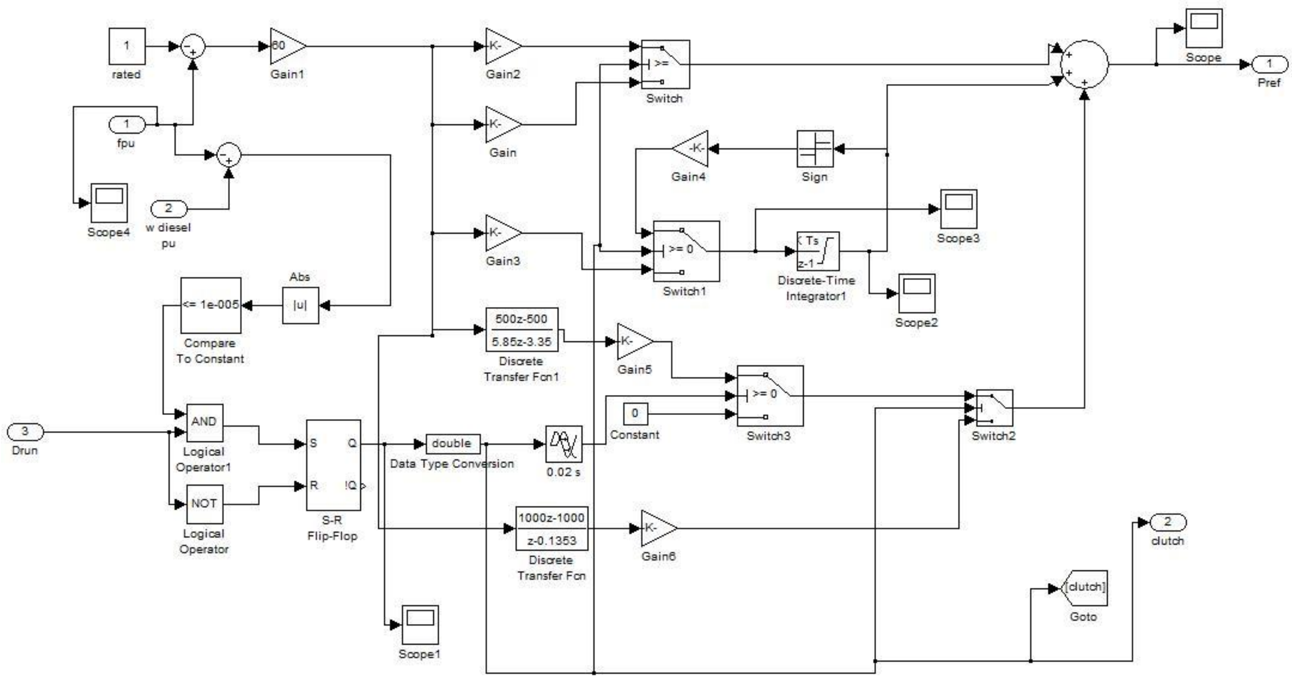


*Fig. 4. APR schematic*

The BESS/DL sharing defined in (3) and (4) is performed within the Power Sharing Block of Fig. 2, according to the following equation:

$P_{D\_REF} = 0$ if $P_{REF} \leq P_{S\text{-}NOM}$ [6]

that means that the DL does not actuate unless the positive $P_{REF}$needed is greater than the BESS rated power $P_{S\text{-}NOM}$, guaranteeing that the DL only will dump just the wind power excess that the BESS can not store. So when $P_{REF} > P_{S\text{-}NOM}$, this block assigns to the DL the minimum integer number $X_{D\text{-}REF}$ which verifies $X_{D\text{-}REF\_}P_{STEP} > P_{REF}–P_{S\text{-}NOM}$ and after this, $P_{S\text{-}REF}$ is defined as $P_{S\text{-}REF} = P_{REF}–X_{D\text{-}REF\_}P_{STEP}$. With these calculations (3) and (5) are always satisfied and the value of $P_{S\text{-}REF}$ is accommodated to take into account the discrete nature of the DL used in this simulation.

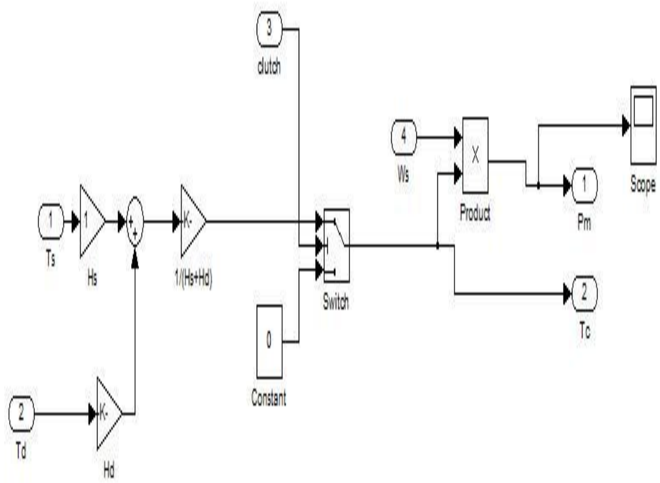


*Fig. Simulink schematic of clutch*

## V. SIMULATION RESULTS

In the graphs presented below the system frequency/SM speed and the DE speed are plotted in pu value in Figs. 4 and 5. The rms voltage in pu value is shown in Fig. 6. The active powers for the WTG, SM, BESS and consumer load are plotted in kW in Fig. 7. The DL does not actuate during the presented test as the positive $P_{REF}$ calculated in APR block during the test is in the $[0,P_{S\text{-}NOM}]$ range, so that the DL reference and consumed powers $P_{D\text{-}REF}$ and $P_D$ are cero during the test and therefore $P_D$ is not plotted. Fig. 7 shows the active powers as being positive when produced and negative when consumed, so that the sum of active powers in Fig. 7 is null whenever the power system is in equilibrium. At the starting point in t = 0, the WDHS is in WO mode (WD/ WO_ = 0), so the DE speed is 0.3 pu (Fig. 4) as it has been explained, the clutch is disengaged (CLUTCH = 0), the input torque to the SM is zero and the WO PID regulator controls system frequency. The active powers (Fig. 7) in the load and BESS are _50 and _42 Kw (consumed) respectively. The wind speed is 8 m/s and the active power produced by the WTG is 92 kW, being the system in equilibrium. The battery initial SOC is 50%.

 

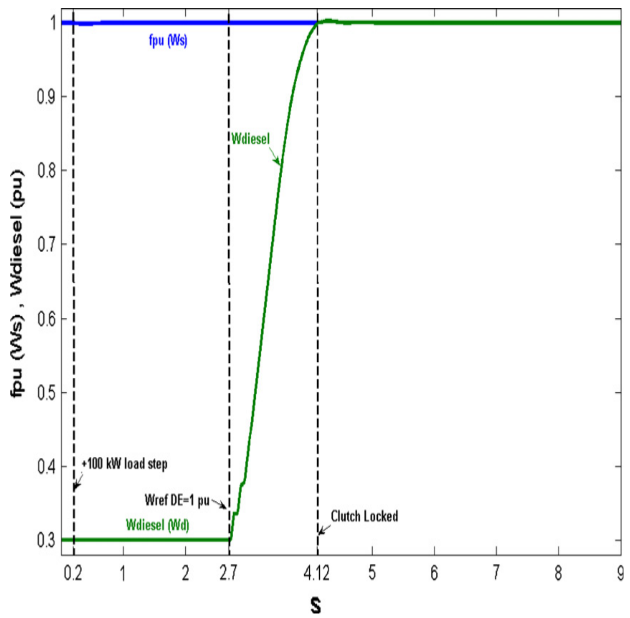


*Fig. 4. System frequency per unit and diesel engine speed per unit.*

5.1 Frequency regulation in WO mode

Fig. 7 shows the load step, how the BESS changes from consuming _42 kW to supplying 58 kW and a transient in the WTG active power with minimum and maximum during oscillations of 78 and 192 kW respectively. During the transient the minimum frequency pu is 0.9985 (Fig. 5) and the RMS voltage pu minimum and maximum are 0.9921 and 1.0038 respectively (Fig. 6). In the steady state reached at t = 1.727 s, the WTG produced active power stays at the same initial value (92 kW) as the wind speed has not changed and the BESS supplies the active power deficit to the consumer load. Starting at the initial state, a positive step of 100 kW in the load is applied in t = 0.2 s. by closing the three phase breaker 3PB shown in Fig. 2, so that the total load (175 kW) is greater than the WTG produced power

5.2 WO to WD mode Transition

As this situation with the BESS producing power can not be permanent,in t = 2.2 s. the WD/WO_ block in Fig. 2 changes to ‘‘1’’, ordering to the DE to reach rated speed and to engage the clutch when conditions are met. The WD/WO_ signal is delayed 0.5 s, so in t = 2.7 s the speed

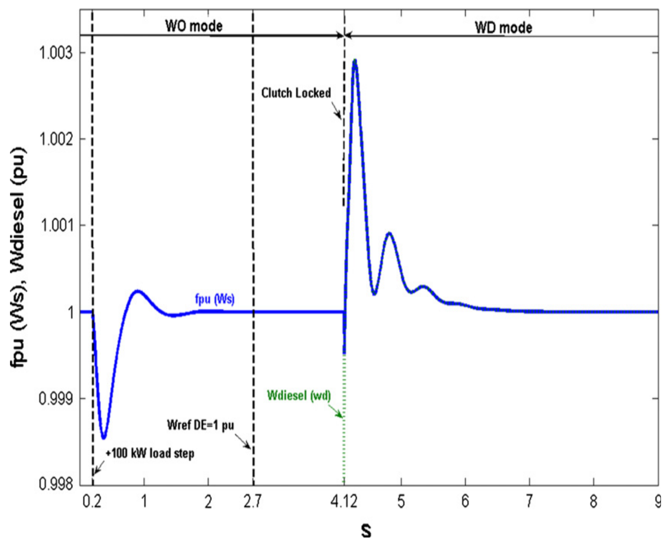


*Fig. 5. Closer view of system frequency per unit and diesel engine speed per unit*

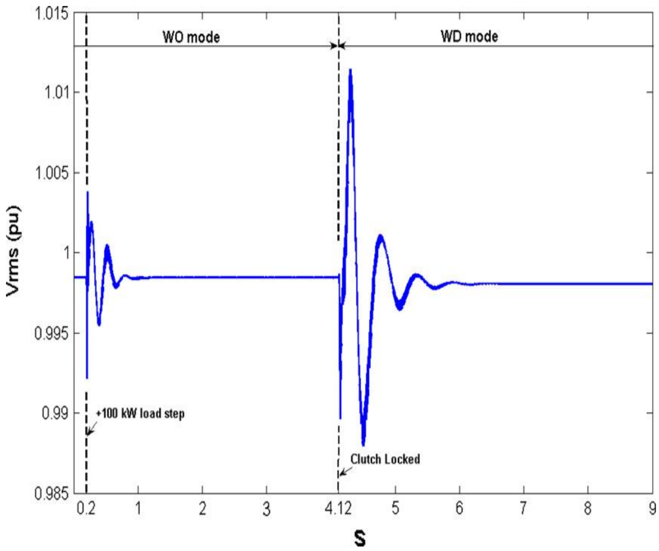


*Fig. 6. RMS voltage per unit.*

reference to the diesel speed controller changes from 0.3 to 1 pu and since this instant the DE begins to accelerate. As it can be seen in Fig. 4 the DE speed increases and when the DE-SM slip is less than 0.002 pu at t = 4.11 s, the CLUTCH output from the APR block changes to 1. With CLUTCH = 1 the Friction Clutch Block changes from disengaged to engaged state, so the DE starts to transfer torque to the SM and the APR changes the WO PID regulator to the WD PD regulator, changing the proportional and derivative constants, the derivative filter and ramping down the WO integral part with the 150 kW/s slope.

The VRMS pu response in Fig. 6 has a 1.0114 and 0.9879 maximum and minimum peaks respectively during the transient after the clutch engages. The WTG active power in Fig. 7 presents a minimum and maximum during oscillations of 65 and 122 kW respectively, but its value at steady state is 92 kW as the wind speed has not changed. Also Fig. 7 shows that the consumer load active power overshoots due to the system voltage variations as the consumer load is purely resistive. The SM runs with zero input power until the clutch engaging instant so the active power supplied by the SM is around 0 in that interval. After the clutch locked instant the DE and SM runs behaving as if they were mforming one axis, with the DE transferring the necessary torque to the SM to take the system frequency to 1 pu and the SM active power shows in that interval over/under shooting with values of 75 and 56 kW respectively.

 

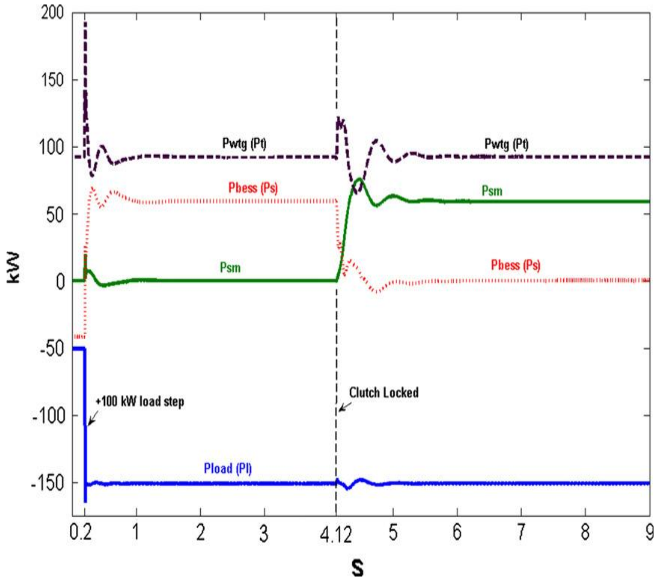


*Fig. 7. WTG, BEES, SM (DG) and load active powers (positive when produced).*

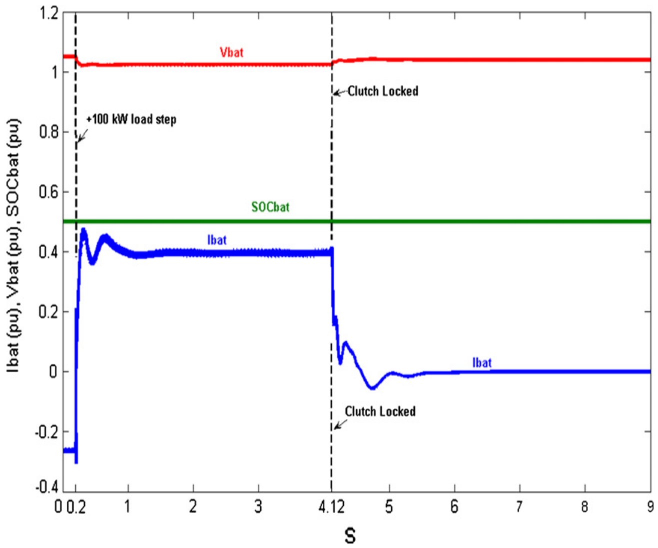


*Fig. 8. Normalized battery current, voltage and SOC.*

The battery current is considered positive when discharging and negative when charging. The battery current in Fig. 8 looks like a scaled version of the BESS active power in Fig. 7. This is so because of the small variations in the battery voltage during the simulation. Initially Ni-Cd battery absorbs charging current of _0.265 pu storing the wind power excess. After the positive 100 kW load step in t = 0.2 s, Ni-Cd battery start to supply discharging current with a maximum of +0.4784 pu, until steady state is reached in t = 1.727 s where discharging current is +0.395 pu.

## VI. CONCLUSIONS

The models for all the WDHS components have been presented. The control system has as inputs the shaft speed of the DE and SM and applies a PID regulator in WO mode and a PD regulator in WD. The presented high penetration WDHS has been modelled and simulated using MATLAB/Simulink environment The first part of the simulation covers the WO mode with the system response to a 100 kW positive load step and shows how the BESS changes from consuming the active power excess to supplying the active power deficit. The second part shows the transition from WO to WD mode by engaging the clutch in the DG, in order to substitute the BESS with the DE as the active power source.

In both simulations the BESS under the command of the APR smoothes the transient and speeds up the system response.

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