Journal of Engineering Science and Technology
Vol. 12, No. 10 (2017) 2826 - 2838

TRANSIENT ANALYSIS OF WIND DIESEL POWER SYSTEM WITH FLYWHEEL ENERGY STORAGE

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Abstract

Wind-Diesel Hybrid power generation is a viable alternative for generating continuous power to isolated power system areas which have inconsistent but potential wind power. The unpredictable nature of variable power from Wind generator to the system is compensated by Diesel generator, which supplies the deficit in generated power from wind to meet the instantaneous system load. However, one of the major challenges for such a system is the higher probability of transients in the form of wind and load fluctuations. This paper analyses the application of Flywheel Energy storage system (FESS) to meet the transients during wind-speed and load fluctuations around high wind operation. The power system architecture, the distributed control mechanism governing the flow of power transfer and the modelling of major system components has been discussed and the system performances have been validated using MATLAB /Simulink software. Two cases of transient stages around the high wind system operation are discussed. The simulation results highlight the effective usage of FESS in reducing the peak overshoot of active power transients, smoothes the active power curves and helps in reducing the diesel consumption during the flywheel discharge period, without affecting the continuous power supply for meeting the instantaneous load demand.

Keywords: Diesel-generator, Wind-generator, Hybrid system, Dump load, Flywheel and energy storage system.

1. Introduction

An autonomous Wind-Diesel Hybrid power system (WDHS) has two sources that can provide active power to system load namely the Wind Generator (WG) and diesel generator (DG). The system can work in three modes of operation, based on the active source available in the instant of generating power viz Window only (WO) mode,

Nomenclatures

A	Area swept by wind turbine blades , m^2
C_p	Power coefficient of wind turbine
f	System frequency, Hz
I	Polar moment of inertia of flywheel, $kg.m^2$
P_L	Load demand, kW
v	Wind speed, m/s

Greek Symbols

$\omega(t)$	Instantaneous speed of flywheel, rpm
ω_{max}	Maximum /rated speed of flywheel, rpm
ω_{WT}	Angular speed of wind turbine shaft, rpm
ρ	Air density, kg/m^3
$\acute{\eta}$	Efficiency of flywheel

Abbreviations

DG	Diesel generator
DL	Dump load
DO	Diesel only (mode)
FESS	Flywheel energy storage system
FW	Flywheel
PRC	Power regulator control
WO	Wind only (mode)
WD	Wind diesel (mode)
WDHS	Wind diesel hybrid system
WG	Wind generator

Wind-Diesel (WD) mode and Diesel only (DO) mode. In WO and DO modes, the lone active power source is Wind Generator (WG) and Diesel Generator (DG) respectively.

In WD mode, the total active power for the system is provided by WG and DG combination, since WG alone could not meet the system power demand due to insufficient wind speed. The term wind penetration ratio denotes the contribution of active energy from WG in meeting the total energy demand of the system for the period of analysis. Wind penetration ratio is defined as the ratio of total energy contributed from wind energy in meeting the load demand to the total energy requirement for the period of analysis (normally taken on yearly or its fractional basis). Unlike Diesel power, Wind power is uncontrollable in nature as it almost depends on the instantaneous wind speed for the selected WG design. To enhance the wind penetration ratio, the excess power stored during the high wind period (WO mode) needs to be stored in suitable Energy Storage System (ESS) for later use. Moreover, ESS also helps in tackling the transient stages associated with power fluctuations from WG (including the mode transitions) thereby ensuring stable, quality and continuous power throughout the assessment period.

This paper discusses the charge-discharge process of Flywheel Energy storage system (FESS) and a control strategy to utilise its stored energy for reducing the power transients during a sudden additional requirement of instantaneous power when the flywheel (FW) is in fully charged state (transient period during post-WO mode of operation). The reduction in DG fuel intake during the period is also discussed. Two cases of post-WO mode transients are discussed in the paper and the power system performance has been validated using MATLAB/Simulink software. The first case deals with the transient period during a sudden reduction in wind speed and the second case deals with a sudden increase in instantaneous load demand, prompting the system to move from WO to WD mode of operation for both. The system architecture and the flow of control signals in it are discussed in section-3. The mathematical modelling of major system components is discussed in section-4. The simulation schematics and the simulation results/analysis are discussed in section-5.

2. Review of Previous Works

The improvement of dynamic analysis of WDHS and its various control strategies has been dealt with in previous research publications. Conventionally, batteries are the preferred option as Energy Storage System (ESS) for such systems, mostly due to its mature technology. The usage of Battery based energy Storage system (BESS) in producing a smooth transition from WO to WD mode are explained by Sebastián et al. [1, 2]. Pena et al. [3, 4] describes the control strategy and performance investigation of WDHS using doubly fed induction generators (DFIG). Although Flywheel (FW) based ESS is an emerging technology, it offers better characteristics in terms of higher efficiency and compactness (than BESS). The comparison between FESS and BESS are discussed by Arghandeh et al. [5] and the advantages of FESS over the later are highlighted. FESS have higher efficiency and its operational cost is lesser than BESS (due to lower cooling system requirements, low chances for internal fault, reduced maintenance cost and increased life which is normally as high as 15-20 years). Moreover, FESS is a better option for the system, if the geographic location suffers frequent wind fluctuations around high wind region (corresponding to the instantaneous system load demand), as flywheel can utilise the high wind situation for storing energy. The design of flywheel depends on the historical data of wind speed for the location. Carrillo et al. [6] discusses the comparative study of various flywheels. Sebastián et al.[7] has listed the various applications of FESS like aerospace and traction. The simulation results shown in the paper highlights the fact that FESS can be used for smoothing the wind power during sudden changes in load.

However, the studies on the application of FESS on isolated WDHS are limited and its effectiveness for usage in various transient conditions was not analysed in previous literatures. One of the important priorities in such a system is to minimize the transient power fluctuations during post WO mode of operation and also reduces the generation of power from DG during the FW discharge period (without compromising on instantaneous power to meet the system load demand). The power fluctuations due to inconsistent wind speed (for input to Wind Turbine) is also major concern for autonomous WDHS micro-grid. The paper discusses the use of FESS to meet the above two problems (along with a typical control strategy), which are not been investigated in previous studies on the subject. The effect of FESS to reduce the above problems has been investigated and validated by simulation using MATLAB /Simulink software.

3. Power System Architecture and Flow of Control Signals

The power system architecture is shown in Fig. 1. The positive power sign indicates generation of power and negative sign indicates the consumption /utilisation. The system has four main modules as given below

i. Wind-Generator (WG) module consisting of wind turbine which produces mechanical power based on the instantaneous wind speed and is coupled to an induction generator.

ii. Diesel Generator (DG) module consisting of Diesel Engine coupled to salient pole synchronous generator which works in isochronous mode of operation.

iii. Flywheel (FW) module consisting of Flywheel coupled to a rotating machine, which can act as both generator and motor, depending on the nature of instantaneous torque input. Normally Induction, Permanent magnet or DC machines are used for the purpose, although the choice has little impact on the conclusions arrived in the paper. For convenience of simulation, DC machine has been used, as it reduces the power electronics complexity in the control circuitry. The machine is connected to micro-grid through a power electronic (PE) sub-module. For the machine to act as motor (during charging period of flywheel), the PE module acts as a rectifier converting the ac power from grid to dc. Similarly, for the action of machine as generator (during discharging period of flywheel), the PE module act as an inverter converting the dc power from generator to ac and feed to the system. The power is taken positive during the discharging of power from FW and negative during its charging duration.

iv. Load module denotes the instantaneous load demand at consumer side where majority of active power generated in the system gets consumed. For stable operation of the network, the total active power generated should be same as that consumed. The mismatch in generated and consumed power will produce a tendency to alter grid frequency. An increase in the generated power over power consumed will lead to an increase in frequency and the vice versa situation will cause a tendency to reduce system frequency.

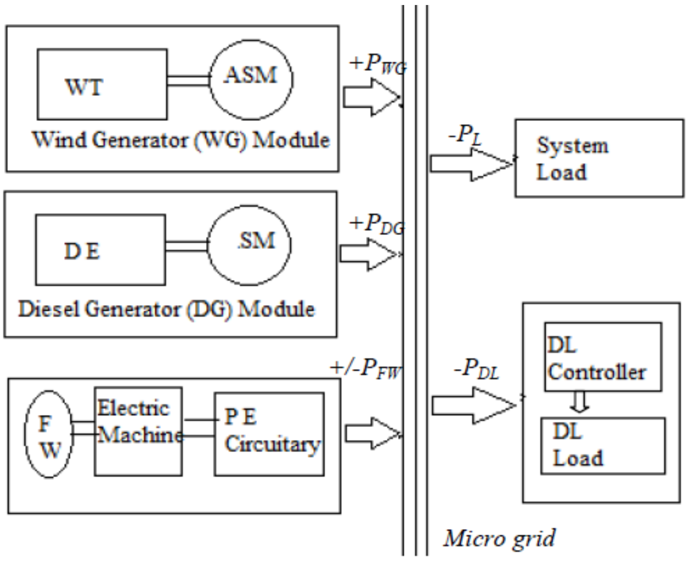

Fig. 1. Block diagram of WDHS power system architecture.

The Block diagram depicting the system control architecture is shown in Fig. 2. The main module regulating the flow of control signals in the system is the power regulator control (PRC) Module, which controls and coordinates the power flow to /from other three modules (DL, FW and DE modules), as shown. The input to the module is the system frequency (f), which will be sensed by the system sensors embedded inside it. The frequency is compared with a preset reference frequency value (f*) and the error (δ_e) obtained is amplified using a Proportional-Derivative (PD) controller. The Proportional part of the controller helps to amplify the error frequency to a designed higher level and derivative part ensures the adequate speed of response without exceeding the stability margins. The flowchart highlighting the control signal flow is illustrated in Fig. 3. The PRC module will be activated when the frequency error exceeds the tolerance limits. The positive error indicates an increased instantaneous power generation in the system (than the corresponding instantaneous system load) and the negative error indicates a lower instantaneous generation.

When the error is positive, the flywheel module will be put in charge ('C') mode and the rotating machine will use the grid energy to rotate/charge the flywheel to its maximum rated speed. The power electronics converters (PEC) attached to the module will ensure that the machine is provided with the designed input power for acting as the motor and charge the motor (for example, if dc machine is used, the PEC converts the grid ac-power into dc, in accordance with the designed ratings, and the machine will use the power to run the FW).

To compensate the excess generation (after introduction of FW) beyond instantaneous system load, dump load actuators are activated, which introduces the required dummy loads into the system and the system frequency is brought back to the tolerance limits. If the system frequency error is negative beyond the tolerance limits, the PRC module will check whether the FW module have the minimum threshold power for power discharge. If available, the PRC will activate the FW module controller for putting it in discharge ('D') mode.

The PRC will enable the smooth discharge of FW power to the grid in the designed fashion, which will be explained in later sections (For example, if dc machine is used, the PRC will convert the dc power - generated using the mechanical energy from FW – to ac and feed to grid).

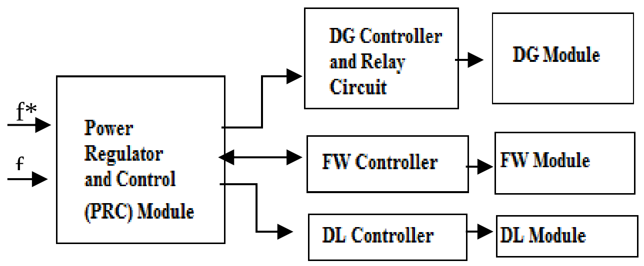

Fig. 2. Power regulator signal flow diagram.

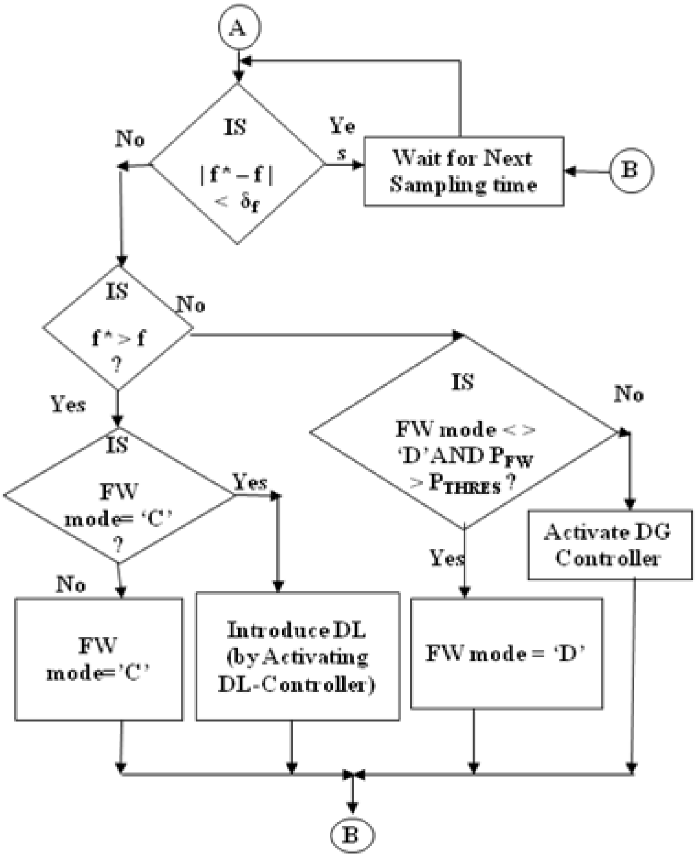

Fig. 3. Flowchart on the flow of control signals.

4. Mathematical Modelling of Major Power System Components.

The Wind turbine (WT) converts the captured wind speed into corresponding mechanical rotational energy for running the asynchronous machine (ASM) for producing useful electrical energy (EE). If ρ is the air density (in kg m $^{-3}$), A - the area swept by WT blades and Cp is a factor called power coefficient (whose value influenced by the ratio of WT shaft speed and wind velocity), then the output power of WT [8, 9] is given by Eq. (1).

$$P_T = \frac{1}{2}\rho A v^3 C_p \tag{1}$$

The useful mechanical torque (T_{wt}) can be obtained from the useful shaft power (P_{wt}), after reducing the losses, is given by Eq. (2).

$$T_{wt} = \frac{p_{wt}}{\omega_{wt}} \tag{2}$$

The Diesel Generator (DG) is a combination of Diesel Engine (DE) and Synchronous machine (SM) [10]. It is isochronous in nature and runs at constant speed. The block diagram of DE is shown in Fig. 4. The DE senses the difference in reference and actual speed of DG and the speed error generates the control signal to actuate the combustion block. The combustion block initiates steps to change the position of fuel valve and thereby varying the injected fuel rate, for restoring the DE speed to reference speed value.

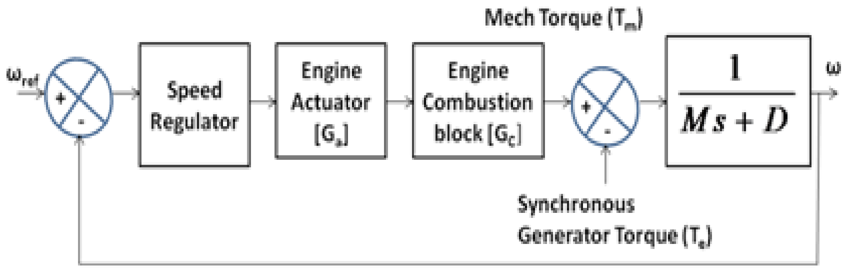

Fig. 4. Block diagram of a DE model.

The transfer gain function of DE- actuator is given by Eq. (3) [11-13].

$$G_a = \frac{(1+T_4.s)}{s\,(1+T_5.s)(1+T_6.s)} \tag{3}$$

The transfer gain function of DE- Combustion block is given by Eq. (4).

$$G_c = \frac{K.(1+T_3.s)}{(1+T_1.s+T_1.T_2.\,s^2)} \tag{4}$$

T_1, T_2, T_3, T_4, T_5, T_6 are time constants.

The generalised modelling concepts of various electrical machines are elaborated in [14-17]. References [18-19] discussed the mathematical modelling of multi-phase induction machine. The corresponding Simulink models are available in the Simulink library [20-21].

The flywheel is a mechanism to store rotational energy. The block diagram of flywheel energy storage module is shown in Fig. 5. During WO mode duration, the excess energy (than instantaneous system load demand) generated from the WG is utilised to run a rotating machine coupled to flywheel for rotating to its rated speed. The power from WG is first fed into PEC module, which regulates it to the designed specifications/format of machine. The energy (E) stored in the flywheel is influenced by the moment of the polar inertia (I) and the angular speed of rotation of flywheel (ω), given by following Eq. (5) [3, 22].

$$E = \frac{1}{2}.\,I.\,\omega(t)^{\,2} \tag{5}$$

The energy stored reaches maximum when its rotational speed becomes the designed rated value. During WD mode, the flywheel energy is discharged into the grid for reducing the power generated from the DG (without affecting the continuity of instantaneous power requirements). The FW speed during power discharge has two regions of operation – viz constant speed region and exponential region. During the constant speed region (with time duration T), the FW speed will be almost constant at its initial rated speed (ω_{max}) at the corresponding discharge interval. During the exponential region, the speed decreases exponentially (the slope determined by Eq. (6)). The discharge speed, with time constant k (influenced mainly by the moment of inertia) can be written mathematically [3, 6, 22] as

$$\begin{aligned} \omega(t) &= \omega_{max} && t \le T \\ &= \omega_{max} e^{-Kt} && t > T \end{aligned} \tag{6}$$

The energy during discharge is influenced by the instantaneous speed (based on above equation) and is given by Eq. (7).

$$E_{dis} = \frac{1}{2}.I.\omega(t)^{2} \tag{7}$$

Substituting the value of speed from Eq. (6) in to Eq. (7) and differentiating with respect to time (with $\acute{\eta}$ as flywheel efficiency) yields the power during the discharging interval shown in Eq. (8).

$$\begin{aligned} P &= P_{max} && t \le T \\ &= P_{max}\ \eta'\ \omega_{max}^{2}\ e^{-k.t} && t > T \end{aligned} \tag{8}$$

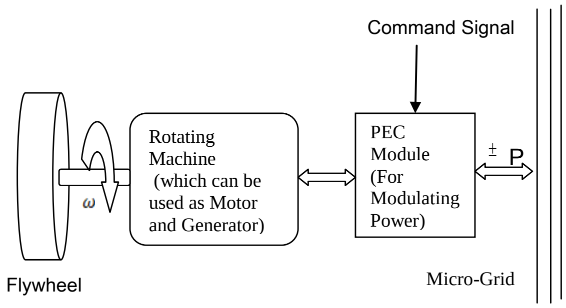

Fig. 5. Flywheel Energy storage system module.

5. Simulation Schematics and Result Analysis

The MATLAB/Simulink schematic diagram of WDHS with Flywheel energy storage system is shown in Fig. 6. As described in section-1, the whole system is divided into five module blocks. The Diesel Engine (DE) and coupled Synchronous machine are enclosed in DG block. The Wind-turbine and coupled ASM constitute the WG module block. The Flywheel coupled to rotating machine (which can act as both generator and motor) are enclosed in FESS module block. For simulation simplicity, the rotating machine used is of dc type. The DL block incorporates the three-phase resistance block for curtailing any tendency to increase the system frequency. The value of resistance to be introduced for it depends on the control system signal generated from discrete frequency regulator.

Two cases of wind fluctuations around the WO mode of operation are discussed here. In all the cases, the effect of flywheel in reducing the peak overshoot, as well as the reduction of power from DG (as a percentage of power produced from it without the use of FESS) is computed. The savings in power (neglecting the initial transients during the transition) from DG during the flywheel discharge exponential region from time t_1 to t_2 can be calculated as follows in Eq. (9).

$$\delta E_{DG} = P_{DG}.(t_2 - t_1) - \int_{t_1}^{t_2} P_{DG}' \, e^{-kt} \, dt \qquad (9)$$

where P_{DG} is the steady state average power consumed by DG during the interval (without FESS), P_{DG}' is the DG power at time instant t_2 (while using FESS).

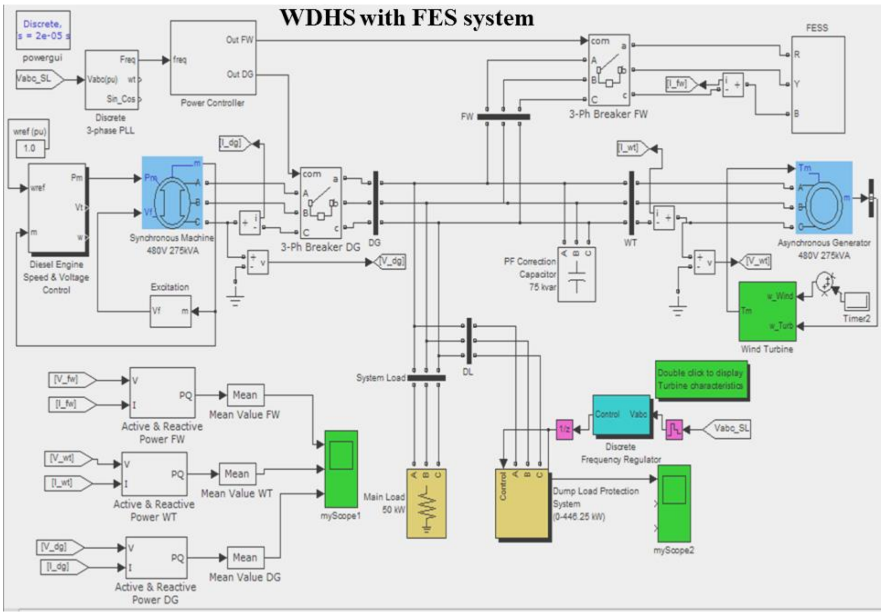

Fig. 6. Simulink schematics of power system.

5.1. Analysis of simulation results

Case I – Transient stage during sudden decrease in wind power forcing system mode change from WO to WD.

The case deals with the transient response when the wind speed suddenly decreases forcing the system to change from WO mode to WD mode of operation. In the simulation, the initial wind speed was at 14.2 m/s and the system was working in WO mode of operation (as the power generated from WG was enough to meet the instantaneous load demand) and by the action of PRC module explained earlier, the FW will be in the fully charged state. At time t=3 seconds, the wind speed was changed from 14.2 m/s to 9.2 m/s and to meet the load demand (which remained constant throughout the simulation) additional generation of power was required (as WG along could not generate the required power). By the action of PRC (in accordance with the flowchart shown in Fig. 3.) the FW starts discharging and the waveforms (wind speed, Power from WG, Power from FESS and Power from DG) during the period is shown in Fig. 7. and Fig. 8. It is observed from the simulation results (shown in Fig. 8.) that the maximum peak overshoot during the transient period decreased by 28.8 % (from

100 kW to 71.2 kW). The total savings in diesel power during the FW discharge period, as per Eq. (9), is found to be 60% (for time period from *t*=3 to *t*=17.85 s).

Case II – Transient stage during sudden load enhancement forcing system mode change from WO to WD mode

This case depicts the situation in which a sudden increase in system loads during the WO mode of operation forcing the system to work in WD mode, resulting in more usage of diesel fuel. As described in the flowchart (Fig. 3.), the FESS will be in the state of fully charged during the WO mode of operation. At time t = 3 s, an additional load of 60 kW is included to the system (to produce a worst form of transients due to load increase, as it occurs instantly), resulting in a cumulative load of 210 kW and forces the system to work in WD mode of operation. Now the FW circuit will be activated by the action of PRC module in accordance with the flowchart said earlier and discharges power into the grid (as per Eq. (8). Figure 9 shows the result of simulation that the maximum peak-overshoot on DG power during the transient period decreases by 86.56 % (to 6.25 kW, instead of 46.5 kW when the system works without FESS). It is also observed from the simulation result that the total energy saving from DG is about 72.88% during the FW discharge period (compared to the situation without FESS).

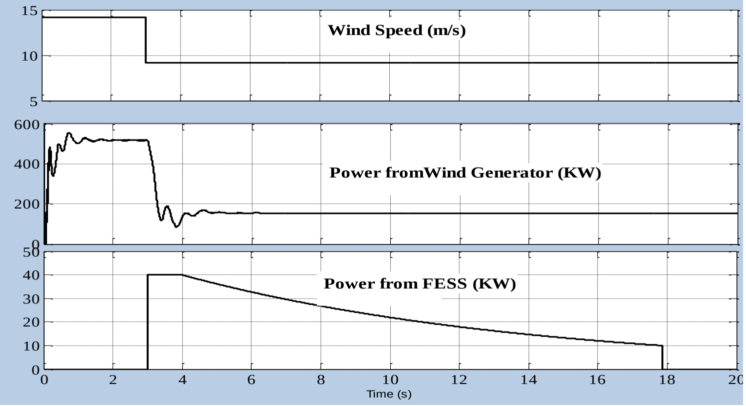

Fig. 7. Behaviour of FESS for case I.

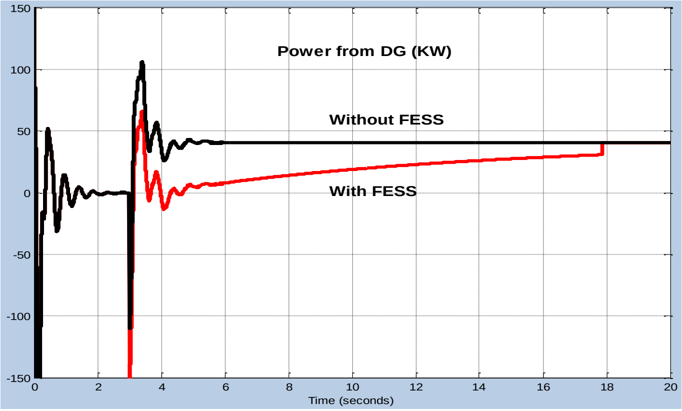

Fig. 8. Power from DG (with and without FESS) for case I.

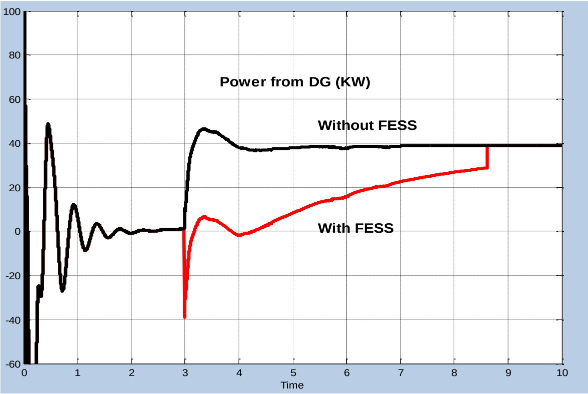

Fig. 9. Power from DG (with and without FESS) for case II.

6. Discussion

The simulation analysis clearly suggests that the flywheel, in addition to the power savings from DG, also helps in smooth transition of active power transfer during the post WO mode of operation of WDHS system. The system frequency is dependent on the active power flow in the system, whereas the system voltage is governed by the reactive power in it. The control mechanism discussed in the paper will ensure that the system frequency will remain constant, as the total active power generated in the system is same as that consumed by it. The deficiency in power generation during post WO mode of operation is compensated by the same generated from FESS (excess power generated if any, will be absorbed by the introduction of dump loads, thereby maintaining the power balance). An IEEE type-1 excitation system [10] is used in the DG, which ensures that the system voltage remains constant (by injecting /absorbing the needed reactive power into the system and ensuring that the total reactive power generated by the reactive power sources will be absorbed by the reactive power sinks in the system). Figure 10 shows that the voltage in the system remains constant (at one per units in both cycles), which is made possible by the action of the exciter system in DG module.

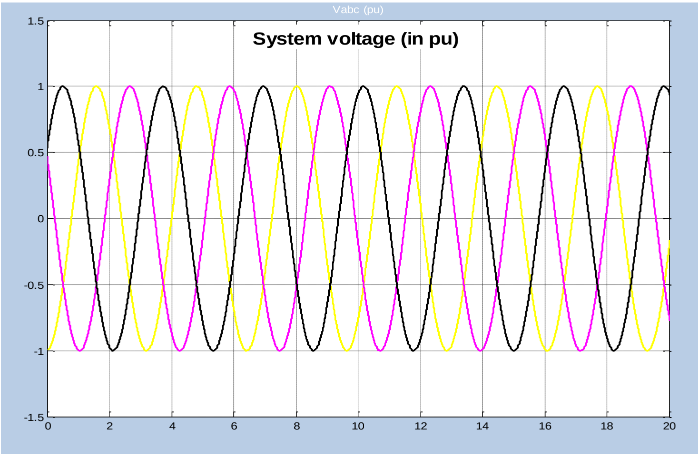

Fig. 10. System voltage (in pu).

7. Conclusions

WDHS is a viable option for providing continuous power especially at isolated locations with potential wind power which is virtually inaccessible to national grid Transient problems at high wind conditions create power fluctuations at the DG side and are one of the major power quality issues in its operation Two cases of such transients are discussed in the paper and the effective application of FESS for the cases have been validated using Simulink software. The discharge pattern of power into grid, the modelling of system components and the effect of FESS on the DG output is analysed /discussed. It is observed that there will be substantial reduction in the maximum overshoot of power transients along with reduction in energy from DG during the FW discharge period (without affecting continuity of power supply). For case I, the maximum peak overshoot during the transient period decreased by 28.8 % and the total savings in diesel power during the FW discharge period was observed as 60%. For case II, the corresponding values were found to be 86.56 % and 72.88% respectively. Reduction of power from DG helps to reduce the share of non-renewable energy in the system and makes the system more environmental savvy.

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