DYNAMIC PERFORMANCE OF WIND-DIESEL POWER SYSTEM WITH CAPACITIVE ENERGY STORAGE

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Abstract—This paper presents an analysis of the dynamic performance of a wind-Diesel power system which operates in isolation from the grid. The simulation studies of the dynamic response are conducted in two different configurations of the power system, firstly, without storage and, secondly, with capacitive energy storage. The frequency and power deviations resulting from a step load disturbance of 1% are presented. It is shown that improvement in the transient responses of the stand alone wind and the hybrid wind-Diesel power system is achieved when capacitive energy storage is included in the systems.

Wind Diesel Capacitor energy storage

SYSTEM PARAMETERS

\[ H_a = 3.5 \, \text{s} \]
\[ H_m = 8.5 \, \text{s} \]
\[ K_{cc} = 16.2 \, \text{Hz/pukw} \]
\[ K_{cd} = 16.5 \, \text{Hz/pukw} \]
\[ Z_{kpc} = 2.0 \]
\[ K_{k1} = 4.0 \]
\[ K_{k2} = 1.25 \]
\[ T_{id} = 0.60 \, \text{s} \]
\[ T_{sd} = 0.041 \, \text{s} \]
\[ K_{si} = 1.4 \]
\[ K_{opc} = 0.08 \, \text{pukw/deg.} \]
\[ f_{base} = 0.01 \, \text{pukw} \]
\[ \Delta P_e = 0.0 \, \text{pukw} \]
\[ P_e = 350 \, \text{kW} \]

CES UNIT DATA

\[ C = 1.0 \, \text{F} \]
\[ R = 100 \, \text{ohms} \]
\[ E_{dc} = 2.0 \, \text{kV} \]

INTRODUCTION

Although electrical energy is environmentally the most benign form of energy, its production is routed through conventional fossil fuel burning or through nuclear energy and, wherever possible, through hydro-resources. All of these, in addition to other disadvantages, give rise to environmental issues of varied natures. It is, therefore, necessary to consider the problem of electrical energy generation and the environment jointly, so that the growing need of electricity for industrialization would be met with minimal environmental degradation. One of the solutions is to utilize wind energy in favourable sites, which are often remote from centralized energy supply systems. Since wind power varies randomly, there must be a stand-by power source to meet load demand. A wind-Diesel system is one of the hybrid systems utilizing more than one energy source. A hybrid wind-Diesel system is quite reliable because the Diesel part acts as a cushion to take care of variations in wind speed and would always provide power equal to load power minus wind power.
Wind energy plays a very important role in the generation of electricity from non-conventional and renewable energy sources. Large numbers of machines in various sites and configurations have been developed for electric power generation in the kW and MW range.

Wind electricity generation in the range of 50 to 300 kW capacities has been used in grid connected wind farms. At present, this mode of application is very important. Wind electricity generation in the middle range of 20 to 100 kW has been used in stand alone modes supplemented by power from Diesel generator sets.

Although a large number of concepts for wind electricity generators have been introduced from time to time, there are, basically, two designs which have been put to practical application. One is the conventional horizontal axis, propeller type wind turbine with two or three aerofoil blades. These are the most popular and extensively used machines. The other is the Darrius type vertical axis wind turbine which is of relatively recent origin. These machines are still in the development stage and are not so common.

**DIGITAL COMPUTER MODEL OF WIND-DIESEL SYSTEM WITH CAPACITOR ENERGY STORAGE UNIT**

The design and operation of wind stand-alone and wind-Diesel isolated power generation systems presents a few problems. The loads on the system change from time to time, and there will be times when no wind blows. For the wind stand-alone power system, the need to introduce a storage medium to meet the load demand during such conditions is essential. There must be some form of energy storage to meet the load when the wind is not blowing. It then remains to determine how long this stored energy needs to last and how it should be stored.

In the case of the wind-Diesel power system, the Diesel generator must, therefore, be sized to meet the maximum demand, plus an allowance for growth, when no wind blows. With the capacity of the Diesel generator fixed, then under favourable wind conditions, the wind turbine can be used to reduce the load on the Diesel generator, thereby saving fuel. In extreme cases, given sufficient wind and a large enough wind turbine, the Diesel generator can be shut down and the electricity demand met by the wind turbine alone.

When it comes to deciding how this energy should be stored, the use of a capacitor energy storage unit for load levelling/damping purposes is one of the options, and its application to a wind-Diesel power system is presented herein.

**VARIOUS TYPES OF ENERGY STORAGE**

Superconducting magnetic energy storage (SMES), batteries and capacitors have been suggested as storage units for improving the dynamic performance of hybrid wind-Diesel power systems without a grid connection.

Batteries have the highest energy storage density, of the order of $10^8 \text{ J/m}^3$. The SMES has a slightly lower storage density, around $10^7 \text{ J/m}^3$. Capacitors manufactured with present technology have a storage density of only $10^5 \text{ J/m}^3$.

The dielectric losses and low energy density of capacitors make them less attractive as a bulk energy storage device capable of load levelling during large generation loss incidents. However, a small rating capacitive energy storage (CES) can effectively damp the power-frequency oscillations caused by small perturbations in the real power load.

The advantages of a CES unit are that it is practically maintenance free and does not cause any environmental degradation. The operation of the CES unit is quite simple and less expensive, compared with the SMES which requires a continuously operating liquid helium refrigeration system.

**CONFIGURATION OF CAPACITIVE ENERGY STORAGE IN WIND POWER SYSTEM**

Figure 1 shows the basic configuration of a CES unit in the wind generator power supply system. The storage capacitor is connected to the AC grid through a power conversion system (PCS) which includes an inverter/rectifier. The storage capacitor may consist of many discrete capacitors
connected in parallel, having lumped capacitance 'C', as represented in Fig. 1. The resistance R connected in parallel to the capacitor is the equivalent resistance of the capacitor bank to represent its dielectric and leakage losses.

The capacitor can be charged to a set value of voltage (which is less than the full charge) from the utility grid during normal operation of the grid.

A reversing switch arrangement using gate-turn-off thyristors (GTO) is provided to accommodate the change of direction of current in the capacitor during charging and discharging, since the direction of current through the bridge converter cannot change. In the charging mode switches S1 and S4 are on and switches S2 and S3 are off. In the discharging mode switches S2 and S3 are on and S1 and S4 are off.

The use of capacitor voltage deviation feedback

It is desirable to restore the capacitor voltage to its rated value after a system disturbance so that it can respond to the next load disturbance. The CES unit has a natural tendency to voltage restoration, which is a very slow process, and artificial enhancement of the rate of restoration is required.

The use of capacitor voltage deviation feedback in the CES control loop is suggested here. The capacitor voltage deviation can be sensed and used as a negative feedback signal in the CES control loop to achieve quick restoration of the voltage. Then, with frequency deviation as the control signal, we get

\[ \Delta I_d = \frac{1}{1 + ST_{ac}} (K_v \Delta F - K_{ac} \Delta E_d) \]  

(1)

where \( \Delta L_d \) is the thyristor converter output current deviation, kA; \( K_{ac} \) is the gain corresponding to \( \Delta E_d \) feedback, kA/kV; \( K_v \) is the gain corresponding to \( \Delta F \) feedback, kA/kV; \( \Delta F \) is the frequency deviation of the wind turbine (\( \Delta \omega_t / 2\pi \)), Hz; \( \Delta E_d \) is the thyristor converter voltage deviation, kV; S is the Laplace complex frequency operator.

The block diagram representation of such a control scheme is shown in Fig. 2. It may be appreciated that, during the first few seconds after the occurrence of the disturbance, the second term in the above equation does not have any appreciable magnitude because \( \Delta E_d \) is small. With the increase of \( \Delta E_d \), the term \( K_{ac} \Delta E_d \) becomes appreciable in comparison to \( K_v \Delta F \). This reduces the current deviation and restores the current to normal. Thus, when the power system requires

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**Fig. 1. CES unit configuration.**
the extra energy in the first few seconds after the disturbance, it is supplied as before. The current restoration process becomes operational after some time, when the current has deviated to a considerable extent.

Power modulation in CES units

When there is a sudden rise in the load demand, the stored energy is almost immediately released through the power conversion system (PCS) to the wind generator as line quality AC. As the governor and other control mechanisms start working to set the wind generator to the new equilibrium conditions, the capacitor charges to its initial value of voltage. The action during the sudden release of loads is similar. The capacitor is immediately charged towards its full value, thus absorbing some portion of the excess energy in the system, and as the system returns to its steady state, the excess energy absorbed is released and the capacitor voltage attains its normal value.

To show the effect of the CES unit on the Automatic Generation Control (AGC), a small rating CES unit having 3.8 MJ maximum storage capacity is considered. The capacitor voltage must not be allowed to deviate beyond certain lower and higher limits. If the capacitor voltage goes too low during a system disturbance and if another disturbance occurs before the voltage returns to normal, more energy will be withdrawn from the capacitor; this may lead to discontinuous control. To overcome this problem a lower limit is set for the capacitor voltage, say 30% of the rated value. The upper limit of the capacitor voltage is limited by factors such as capacitor rating, insulation level of the capacitor and the rating of the converter bridge.

The normal operating point of the capacitor is set such that the maximum allowable energy absorption equals the maximum allowable energy discharge. This makes the CES unit equally effective in damping the oscillations created by sudden increase or decrease in load. If \( E_{\text{dmax}} \) and \( E_{\text{dmin}} \) denote the maximum and minimum limits of voltage respectively, and \( E_{\text{do}} \) denotes the set value of voltage, then,

\[
(1/2)CE_{\text{dmax}}^2 - (1/2)CE_{\text{do}}^2 = (1/2)CE_{\text{dmin}}^2 - (1/2)CE_{\text{dmin}}^2
\]

\[
E_{\text{do}}^2 = \frac{(E_{\text{dmax}}^2 + E_{\text{dmin}}^2)}{2}.
\]

If \( E_{\text{dmin}} = 0.3E_{\text{do}} \), then \( E_{\text{dmax}} = 1.38E_{\text{do}} \).

Control of CES units

The operation of CES units, that is charging and discharging in the steady state mode and power modulation during the dynamic oscillatory period, is controlled by application of the proper voltage to the capacitor so that the desired current flows into or out of the CES. This can be achieved by controlling the firing angle of the converter bridges.
Neglecting the transformer and converter losses, the DC voltage is given by

\[ E_d = 2V_{do} \cos \alpha - 2I_d R_c \]  

(4)

where

- \( E_d \) = DC voltage applied to the capacitor, kV
- \( \alpha \) = firing angle of thyristor, degrees
- \( I_d \) = current through the capacitor, kA
- \( R_c \) = equivalent commutating resistance, \( \Omega \)
- \( V_{do} \) = maximum open circuit bridge voltage of each 6-pulse converter at \( \alpha = 0^\circ \), kV.

The capacitor is initially charged to its normal voltage, \( E_{do} \), by the PCS. Once the voltage of the capacitor has reached \( E_{do} \), it is kept floating at this voltage by continuous supply from the PCS to compensate for the dielectric and other leakage losses of the capacitor.

The energy stored at any instant is

\[ W_c = \frac{1}{2}CE_d^2 \text{MJ} \]  

(5)

where

- \( C \) = Capacitance of the CES unit, Farad.

Frequency deviation as control signal

The frequency deviation \( \Delta F_i \) of the wind generator is sensed and used to control the CES current \( \Delta I_d \). The incremental change in CES current is expressed as

\[ \Delta I_d = \left( \frac{K_{CF_i}}{1 + ST_{do}} \right) \Delta F_i \]  

(6)

where

- \( \Delta F_i = \Delta w_2 / 2\pi \) expressed in Hz
- \( \Delta I_d \) = incremental change in current of CES unit, kA
- \( T_{do} \) = converter time delay, s
- \( K_{CF_i} \) = gain of the control loop, kA/Hz

\( S \) is the Laplace complex frequency operator and \( i \) is the generator unit number.

MATHEMATICAL MODELLING OF THE WIND STAND ALONE POWER SYSTEM

The functional block diagram of a wind stand alone power system (isolated from the grid) with capacitive energy storage is shown in Fig. 3. It is assumed that, initially, the system is in a steady state characterized by a constant frequency \( w_2 \) and a constant wind turbine input power \( P_w \). In response to a small step function load disturbance \( \Delta P_{load} \) applied to the system, the deviations of these parameters from their nominal steady state values are \( \Delta w_2 \) and \( \Delta P_w \), respectively.

Mathematical model of wind stand alone system without CES

When a sudden change in load occurs, the immediate requirement of extra power demand has to come from the inertia of the generator rotor. Consequently, the generator decelerates and the frequency falls, governed by the following equation

\[ \frac{d\Delta w_2}{dt} = \frac{1}{2H_w} (\Delta P_m + \Delta P_w - \Delta P_{load}) \]  

(7)

where

- \( H_w \) = inertia constant of wind turbine generator system, s
- \( \Delta P_w \) = change in wind power input
- \( \Delta P_{me} \) = change in power output of fluid coupling.

The fluid coupling shown in the block diagram of Fig. 3 transfers the speed difference between the turbine and generator frequency into power. The block corresponding to programmed pitch
control consists of a proportional plus an integral controller. The corresponding equation is

$$\frac{d\Delta x_2}{dt} = K_{p2} \frac{d\Delta x_1}{dt} + K_{p1} \Delta x_1$$  \ ((8)

where

$$\Delta x_1 = \Delta P_{max} - \Delta P_{wtg}$$

and

$$\Delta P_{wtg} = K_{pF}\Delta w_2.$$  

Differentiating the above equation with respect to $t$ and substituting for $\Delta P_{wtg}$ and $\Delta P_{max}$ (maximum power setting: $P_{max}$ is always kept constant, so that $\Delta P_{max} = 0$), we get

$$\frac{d\Delta x_1}{dt} = -K_{pF} \frac{d\Delta w_2}{dt}.$$  \ ((9)

By substituting from equations (7) and (9) in equation (8), we get

$$\frac{d\Delta x_3}{dt} = -\frac{K_{pF} K_{p2}}{2H_w} (\Delta P_w + \Delta P_m - \Delta P_{load}) - K_{pF} K_{p1} \Delta w_2$$ \ ((10)

$$\frac{d\Delta x_4}{dt} = K_{p1} T_{p1} \frac{d\Delta x_3}{dt} - K_{p2} \Delta x_1 - \Delta x_2 = -\frac{K_{p1} T_{p1} K_{p2}}{2H_w} (\Delta P_w + \Delta P_m - \Delta P_{load})$$

$$- K_{p1} T_{p1} K_{p2} \Delta w_2 + K_{p1} \Delta w_2 - \Delta x_3$$ \ ((11)

$$\frac{d\Delta x_5}{dt} = \frac{1}{T_{p2}} (\Delta x_3 - \Delta x_4)$$ \ ((12)

$$\frac{d\Delta P_m}{dt} = K_{p3} K_{pF} \Delta x_5 - \Delta P_m.$$ \ ((13)

Hence, the state variable equations for the wind stand alone system are described in equations (7), (10)–(13).

![Functional block diagram of wind stand alone isolated power system.](image-url)
Mathematical model of wind stand alone system with CES unit

When the model of the CES unit is added to that of the stand alone power system, the input signal to the CES unit is the angular frequency deviation of the wind turbine generation (\(\Delta w_2\)) and the power coming from the CES unit is added at the power summing junction of the model, as shown by the functional block diagram of Fig. 4a. The addition of the CES unit power at the summing junction leads to modification of the state variable equations as follows:

\[
\frac{d\Delta w_2}{dt} = \frac{1}{2H_w} (\Delta P_w + \Delta P_m - P_{\text{load}} - \Delta P_d)
\]  

where \(\Delta P_d\) is the per unit change in converter power, shown as negative since the power into the capacitor is assumed to be positive. \(P_R\) is the rated capacity of the wind generator in kW.

\[
P_d = \frac{E_{gs} \Delta I_d}{P_R} \frac{d\Delta x_2}{dt} = -\frac{K_{pc} K_{p2}}{2H_w} (\Delta P_w + \Delta P_m - \Delta P_{\text{load}} - \frac{E_{gs} \Delta I_d}{P_R} - K_{pc} K_{sp1} \Delta w_2)
\]  

\[
\frac{d\Delta x_2}{dt} = K_{ps} T_p1 \frac{d\Delta x_2}{dt} + K_{ps} \Delta x_2 - \Delta x_3 = -\frac{K_{ps} T_p1 K_{pc} K_{p2}}{2H_w} \left(\Delta P_w + \Delta P_m - \Delta P_{\text{load}} - \frac{E_{gs} \Delta I_d}{P_R}\right)
\]  

\[
+ K_{ps} T_p1 K_{pc} K_{p1} \Delta w_2 + K_{ps} \Delta x_2 - \Delta x_3
\]  

\[
\frac{d\Delta x_4}{dt} = \frac{1}{T_{p2}} (\Delta x_3 - \Delta x_4)
\]  

\[
\frac{d\Delta P_m}{dt} = K_{ps} K_{pc} \Delta x_4 - \Delta P_m.
\]  

The state variable equations defining the voltage and current deviations in the CES capacitors are:

\[
\frac{d\Delta I_d}{dt} = \frac{1}{T_k} [(\Delta I_d - K_s \Delta w_2) - K_{sd} \Delta E_d]
\]  

\[
\frac{d\Delta E_d}{dt} = \frac{1}{C} \Delta I_d.
\]

The state variables for the wind stand alone power system with the CES unit are described by equations (14)–(20). By setting the CES gain parameter \(K_s = 0\), we get the system model without a CES unit.

MATHEMATICAL MODELLING OF WIND-DIESEL POWER

Without CES unit

For the wind-Diesel power system, the governor adjusts the Diesel power through the valve setting of the turbine depending on the frequency deviation signals \(\Delta w_2\) and \(\Delta w_1\), in response to the step load disturbance of 0.01 pu applied to the system.

\[
\frac{d\Delta w_2}{dt} = \frac{1}{2H_w} (\Delta P_w + \Delta P_m - K_{pc} \Delta w_2 + K_{pc} \Delta w_1)
\]  

\[
\frac{d\Delta w_1}{dt} = \frac{1}{2H_o} (\Delta P_1 + \Delta P_{\text{load}} - K_{pc} \Delta w_2 + K_{pc} \Delta w_1)
\]  

where \(H_o\) is the inertia constant of the Diesel engine, s.
Fig. 4. (a) Transfer function model of a wind stand alone power system with pitch control and CES unit. (b) Transfer function model of wind-diesel power system.
As the Diesel governor transfer function is not first order, we define a dummy variable $\Delta P_n$ as,

$$\frac{d\Delta P_n}{dt} = -K_d \Delta w_i \quad \text{as} \quad \Delta w_{ref} = 0 \quad (23)$$

$$\frac{d\Delta P_i}{dt} = 40\Delta P_n - 40\Delta P_i - 40K_D \Delta w_i. \quad (24)$$

Similarly to the wind stand alone power system, the programmed pitch control block consists of a proportional plus as integral controller. Then,

$$\frac{d\Delta x_2}{dt} = ZK_{pc} \frac{d\Delta x_1}{dt} + K_{pi} \Delta x_i \quad (25)$$

where

$$\Delta x_i = \Delta P_{\max} - \Delta P_{\text{req}} = -\Delta P_{\text{wag}}$$

and

$$\Delta P_{\text{wag}} = K_{PC}(\Delta w_2 - \Delta w_1).$$

Substituting $\Delta P_{\text{wag}}$ and differentiating the above equation with respect to $t$, we get

$$\frac{d\Delta x_2}{dt} = K_{FC} \frac{d\Delta (w_2 - w_1)}{dt} \quad (26)$$

$$\frac{d\Delta x_1}{dt} = -\frac{K_{PC}ZK_{PC}}{2H_w}(\Delta P_w + \Delta P_n) + \frac{K_{PC}ZK_{PC}}{2H_D}(\Delta P_i - P_{\text{ref}}) + \left( \frac{K_{PC}ZK_{PC}}{2H_w} + \frac{K_{PC}ZK_{PC}}{2H_D} - K_{PC}K_{pi} \right) \Delta w_1 \quad (27)$$

\[\text{Fig. 5. Wind frequency deviation of wind diesel power system with and without CES unit.}\]
Fig. 6. Diesel frequency deviation of the wind-diesel power system with and without CES unit.

\[
\frac{d\Delta x_3}{dt} = K_{p2} T_{p1} \frac{d\Delta x_2}{dt} + K_{p2} \Delta x_2 - \Delta x_3 = -\frac{K_{p2} T_{p1} K_{PC} Z K_{PC}}{2H_w} (\Delta P_w + \Delta P_m)
\]

\[
+ \frac{-K_{p2} T_{p1} K_{PC} Z K_{PC}}{2H_D} (\Delta P_1 - \Delta P_{\text{load}}) + \left(\frac{K_{p2} T_{p1} K_{PC} Z K_{PC}}{2H_w} + \frac{K_{p2} T_{p1} K_{PC} Z K_{PC}}{2H_D} - K_{p2} T_{p1} K_{PC} Z K_{pl}\right) \Delta w_1 + K_{p2} \Delta x_2 - \Delta x_3
\]

\[
\Delta w_1 - \left(\frac{K_{p2} T_{p1} K_{PC} Z K_{PC}}{2H_w} + \frac{K_{p2} T_{p1} K_{PC} Z K_{PC}}{2H_D} - K_{p2} T_{p1} K_{PC} Z K_{pl}\right) \Delta w_1 + K_{p2} \Delta x_2 - \Delta x_3
\]  

(28)

\[
\frac{d\Delta x_4}{dt} = \frac{1}{T_{pl}} (\Delta x_3 - \Delta x_4)
\]

(29)

\[
\frac{d\Delta P_m}{dt} = K_{p2} K_{PC} \Delta x_4 - \Delta P_m.
\]

(30)

The state variables for the wind-Diesel power system are described by equations (21)–(30).

**With CES unit**

This case is similar to the wind stand alone power system with the addition of a CES unit. As usual, the signal to the CES unit is the frequency deviation of the wind turbine generator \(\Delta w_1\); the power coming from the CES unit is added at the power summing junction of the system model, as shown by the functional block diagram of Fig. 4b.

The resulting system of state variable equations defining the wind-Diesel power system with a CES unit are:

\[
\frac{d\Delta w_2}{dt} = \frac{1}{2H_w} (\Delta P_w + \Delta P_m - K_{PC} \Delta w_2 + K_{TC} \Delta w_1)
\]

(31)

\[
\frac{d\Delta w_1}{dt} = \frac{1}{2H_D} \left(\Delta P_1 - \Delta P_{\text{load}} + K_{PC} \Delta w_2 - \frac{K_{PC} \Delta w_1 E_{soc} \Delta I_d}{P_r}\right)
\]

(32)
\[
\begin{align*}
\frac{d\Delta P_n}{dt} &= -K_D\Delta w_1 \\
\frac{d\Delta P_f}{dt} &= 40\Delta P_n - 40\Delta P_f - 40K_D\Delta w_1 \tag{33}
\end{align*}
\]

\[
\begin{align*}
\frac{d\Delta w_2}{2H_w} &= -\frac{K_{fc}ZK_{pc}}{2H_w}(\Delta P_w + \Delta P_m) + \frac{K_{pc}ZK_{pc}}{2H_D}(\Delta P_f - \Delta P_{load})\left(\frac{K_{fc}ZK_{pc}}{2H_w} + \frac{K_{fc}ZK_{pc}}{2H_D} - K_{fc}K_{pi}\right) \\
&\quad - \frac{K_{pc}ZK_{pc}}{2H_D}\frac{E_{ac}\Delta l_d}{P_r} \tag{34}
\end{align*}
\]

\[
\begin{align*}
\frac{d\Delta x_3}{dt} &= -\frac{K_{p2}T_{pi}K_{fc}ZK_{pc}}{2H_w}(\Delta P_w + \Delta P_m) + \frac{K_{p2}T_{pi}K_{pc}ZK_{pc}}{2H_D}(\Delta P_f - \Delta P_{load}) \\
&\quad + \left(\frac{K_{p2}T_{pi}K_{fc}ZK_{pc}}{2H_w} + \frac{K_{p2}T_{pi}K_{fc}ZK_{pc}}{2H_D} - K_{p2}T_{pi}K_{fc}K_{pi}\right)\Delta w_2 \\
&\quad + \left(\frac{K_{p2}T_{pi}K_{pc}ZK_{pc}}{2H_w} + \frac{K_{p2}T_{pi}K_{pc}ZK_{pc}}{2H_D} - K_{p2}T_{pi}K_{fc}K_{pc}\right)\Delta w_1 \\
&\quad - \frac{K_{p2}T_{pi}K_{pc}ZK_{pc}}{2H_D}\frac{E_{ac}\Delta l_d}{P_r} + K_{p2}\Delta x_3 - \Delta x_3 \tag{35}
\end{align*}
\]

\[
\begin{align*}
\frac{d\Delta x_4}{dt} &= \frac{1}{T_{pi}}(\Delta x_3 - \Delta x_4) \tag{36}
\end{align*}
\]

\[
\begin{align*}
\frac{d\Delta P_m}{dt} &= K_{p3}K_{fc}\Delta x_4 - \Delta P_m \tag{37}
\end{align*}
\]

---

Fig. 7. Wind power deviation of the wind diesel power system with and without CES unit.
\[
\frac{d\Delta I_d}{dt} = \frac{1}{T_{ac}} \left[ -\Delta I_d + K_{PC} \Delta w_2 - K_{ID} \Delta E_d \right]
\]  
(39)

\[
\frac{d\Delta E_d}{dt} = \frac{1}{C} \Delta I_d.
\]  
(40)

**TRANSIENT PERFORMANCE OF WIND-DIESEL SYSTEM**

The dynamic response of the wind-Diesel power generation system was studied under a load perturbation of 0.01 pu/kW. The transient response of frequency and power deviations of the system with and without a capacitor energy storage unit are shown in Figs 5–7. It is shown here that the addition of a CES unit has a considerable effect in improving the dynamic performance of the system.

Figures 5 and 6 show the frequency deviations of the wind (\(\Delta w_2\)) and Diesel (\(\Delta w_1\)) parts of the system, respectively. It is clear from the figures that the frequency deviations are reduced by about 90% with the addition of the CES unit. The settling time is nearly the same, approximately 24 seconds, for both cases.

**CONCLUSIONS**

Improvements in the quality of the transient response of frequency deviations for the wind stand-alone and wind-Diesel isolated power systems can be achieved using a control which monitors the wind turbine and alters the pitch angle of the blades accordingly. The turbine blade angle pitch control has a significant effect on the dynamic behaviour of the system.

The use of a capacitive energy storage unit connected to the system significantly reduces the frequency and power oscillations following sudden load disturbances, as it can share the immediate requirement for extra power. The energy storage requirement is dictated by the capacity of the power area, the anticipated magnitude of load-frequency perturbations and the desired improvement in dynamic performance of the system.

**REFERENCES**