Primary frequency regulation support through deloaded offshore renewable power generators with HVDC-link

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Abstract
Grid operation becomes a challenging task due to the high penetration of uncontrolled offshore renewable power generators into the mainland system through HVDC-link system. As a result, system frequency may quickly go outside the acceptable range under severe frequency events. This paper proposes a coordinated control strategy for linearized models of deloaded offshore renewable power generators with HVDC-link to make contributions in the mainland system during depressed frequency conditions to address the frequency regulation issue. Linearized models are used to obtain the power output from deloaded ORPG by adjusting droop value in proportional to frequency deviation and minimizing the frequency deviation of the mainland system. Inertia control scheme based on utilizing the different capacitors of HVDC-link is proposed to further improve frequency regulation. Adding inertia from HVDC-link helps to minimize the rate of change of frequency deviation. Finally, to improve both frequency deviation and rate of change of frequency deviation, case studies of offshore renewable power generators linking with HVDC in view of abrupt load deviations have been effectively shown on system model to validate the proficiency of control schemes in MATLAB/SIMULINK®.

1 | INTRODUCTION

Rigorous emphasis has been recently drawn on renewable energy source such as wind power generator (WPG) or solar power generator or tidal power generator (TPG) to combat environmental change. In all of them, WPG is getting much attention from researchers to produce electricity [1]. Studies on the stability issues of WPG is going on from long times due to its wide availability, no greenhouse gas releases throughout operation and usages slight land [2]. Also, offshore or onshore WPG is cheaper than conventional power generator (CPG) and it may easily feed electrical power to the mainland system or isolated off-grid locations [3]. On the other hand, oceans cover around two-thirds of the earth’s surface and, hence, TPG being environmentally friendly, is also seen as one of the possible assets to produce electrical power past few years. The predictability of electrical energy from tidal resources in terms of time and location gives it a unique advantage. Also, electric energy from TPG may transfer to the mainland system through undersea cables without environmental impact [4]. In [5, 6], a detailed outline of TPG modelling is discussed. In this method, TPG is seen as a more economically viable option than a traditional fossil fuel-based generating unit to generate electric energy. From the above discussions, both WPG and TPG may be considered as huge sources of electric energy today.

The supply of active power from offshore WPG or TPG to the mainland system through HVDC-link has increased significantly to meet rising energy burdens. However, renewable energy sources do not offer primary frequency support to power system due to usage of power converters. As renewable energy source based power generating unit generates variable active power output and voltage, therefore, it is not possible to connect unit like WPG or TPG directly to the power system. Also, these generating units work at the maximum power point (MPP). As a result, it becomes decoupled from the mainland system and, hence, system frequency may quickly go outside the standard range under large disturbance [7]. Hence, it is essential to design a control scheme to create a power reserve...
margin to render these units to participate in primary frequency regulation, which may be achieved by deloaded operation. To achieve deloaded operation, authors in [8, 9], have shifted the offshore renewable power generator (ORPG) operating point from its MPP to a reduced power point to create reserve power margin. With this reserved power, deloaded ORPG may contribute to primary frequency support and its quantum depends on the droop control parameter [10]. The low value of droop control parameter causes a large amount of power output from ORPG and minimizes frequency nadir very quickly during abnormal conditions. In case of deloaded operation, the turbine speed of ORPG may increase within a permissible range beyond which it may effect the lifespan of the mechanical components. Through pitch angle control, the turbine speed may be prevented from reaching to the overspeed mode [11]. The optimum deloading value of wind turbine is presented in [12]. In [13], frequency control is achieved through fuzzy logic in case of high wind penetration. In [14], the maximum percentage deloading is determined at different values of pitch angle to keep the turbine speed within the permissible range.

Nowadays, the large scale of ORPGs are integrated with the mainland power system through HVDC-link due to the limitation of AC transmission line [15]. Therefore, the droop control strategy cannot be applied directly to ORPG, since these are integrated with the mainland system through HVDC-link. Thereby, making them unaware of the mainland system frequency. As a solution, a communication-free control structure for HVDC-link connecting deloaded WPG and the grid is discussed in [16]. The presented scheme allows primary frequency participation from WPG while evading reliability and security issues of control schemes based on remote measurements. Integration of offshore wind farm with the mainland system through conventional line commutated converter based HVDC-link to improve frequency regulation using available reserve power margin is discussed in [17]. While, wind farm integration with the mainland through full-bridge diode rectifier based HVDC is investigated in [18].

De loaded operation of ORPG only supports to minimize the maximum frequency variations and it is not capable to decrease the rate of change of frequency deviation (ROCOF) during frequency support. The high value of ROCOF may lead to tripping of protection relay and may lead to system instability. In [19], frequency support from HVDC is presented. Small-signal analysis of HVDC based power system is discussed in [20]. [21, 22] suggest frequency control using energy stored in HVDC-link capacitors. HVDC-link contributes in keeping the inertia support at required value. [23] proposes a concept to generate distributed virtual inertia through power converters, which may raise overall system inertia during the transient period and reduces ROCOF of the mainland system under severe disturbance. The inertia of HVDC-link may be designed same as the inertia of synchronous generators [24, 25], however, it may be changed dynamically by the microprocessor during abnormal conditions. In all the above investigations, it is found that primary frequency support to the mainland system is either provided by HVDC-link or ORPG. Therefore, a coordinated control scheme needs to be implemented for the combined frequency support from both ORPG and HVDC-link for the effective load frequency control (LFC) of the power system model. This coordinated response may help to arrest frequency variation before tripping under frequency load shedding relays or generation protection relays.

In the present work, author uses harmonized/coordinated action of inertia control HVDC-link and droop control of ORPGs to improve the overall frequency dynamics of the power system through primary frequency support. For this study, a power system consisting of deloaded ORPG (having both TPG and WPG) connected to the grid via HVDC-link is considered. The paper is structured as follows. In Section 2, the description of inertia support and frequency droop control are presented. Power system modelling is briefed in Section 3. In Section 4, simulation outcomes are discussed and the conclusion is presented in Section 5.

2 DESCRIPTION OF INERTIA SUPPORT AND FREQUENCY DROOP CONTROL

This section investigates WPG and TPG based ORPG with HVDC-link for the primary frequency support through inertia response and droop control.

2.1 Inertia support from HVDC-link

To enhance the system inertia, HVDC-link plays an important role to supply HVDC capacitors energy to mainland system. The voltage variation \( V_{\text{DC}} \) of HVDC-link capacitors depends on the difference between active power of offshore side \( P_{\text{OF}} \) and onshore side \( P_{\text{ON}} \). This may be stated by (1) [25]

\[
C_{\text{DC}} \frac{dV_{\text{DC}}}{dt} = P_{\text{OF}} - P_{\text{ON}},
\]

where \( C_{\text{DC}} \) is the equivalent capacitance (in pu). The value of \( C_{\text{DC}} \) may be calculated as (2) [25]

\[
C_{\text{DC}} = CV_{\text{DC}}^2 / (VA)_{b},
\]

where \( C \) is the total capacitance (in F) and \((VA)_{b}\) is the base value of the system (in MVA). In case of synchronous generator, it inherently increases the power system inertia. Inertia constant \( (Hc \) in s) of the synchronous generator is calculated using swing equation and it may be written as [15]

\[
2H_{c} \frac{df}{dt} = \Delta P_{a},
\]

where \( f \) is the actual system frequency (in Hz) and \( \Delta P_{a} \) is the difference between the mechanical power input and electrical power output (in MW). If system has high \( H_{c} \) then it helps to minimize the maximum frequency deviation during power
imbalance conditions and improves ROCOFD. Generally, value of \( H_s \) of CPG ranges from 2 to 10 s [26]. In order to emulate inertia in (3), (1) may be written as

\[
C_{\text{DC}} V_{\text{DC}} \frac{dV_{\text{DC}}}{dt} = 2H_{\text{DC}} f \frac{df}{dt}, \tag{4}
\]

where \( H_{\text{DC}} \) is the virtual inertia supply by HVDC-link. Linearizing (4) around its equilibrium point and it may be presented in (5)

\[
H_{\text{DC}} = \frac{\Delta V_{\text{DC}} f^o C_{\text{DC}} V_{\text{DC}}}{(2\Delta f_{\text{m}}(V_A)b)}, \tag{5}
\]

where \( \Delta V_{\text{DC}} \) and \( \Delta f_{\text{m}} \) are the maximum allowable voltage deviation and frequency deviation, respectively and \( f^o \) is the nominal frequency. From (4), it is concluded that when mainland frequency drops then the reference of HVDC-link voltage decreases to release its energy to the power system for inertia support. From (5), it is possible to generate large virtual inertia than the inertia generated by the synchronous generator and this may be possible if we increase either any value of \( V_{\text{DC}} \) or \( C_{\text{DC}} \) or \( \Delta V_{\text{DC}} \) (see Figure 1). A higher value of \( \Delta V_{\text{DC}} \) may bring in over modulation problems. Therefore, suitable choice of these parameters is compulsory for effective frequency regulation. A large value of \( H_{\text{DC}} \) may increase system size and cost. Also, ROCOFD relay in the power system is usually set between 0.1 and 1.2 Hz/s. In case of large value of \( H_{\text{DC}} \), value of ROCOFD may exceed the boundary condition and may lead to tripping of relays. It results in a large disruption to the power system. Hence, proper selection of \( H_{\text{DC}} \) is required to get better performance at low cost. As far as the overall system that the HVDC-link and synchronous generator together provide the equivalent system inertia \( (H_{\text{eq}}) \) may be calculated in (6)

\[
H_{\text{eq}} = H_i + H_{\text{DC}} \tag{6}
\]

From (6), it may be concluded that equivalent inertia may improve the overall stability of the system. The values of the parameters of the HVDC-link are listed in Appendix 1.

2.2 | Frequency droop control of ORPG via HVDC-link

In order to let ORPG supports active power in the primary frequency regulation, as like synchronous generator, a frequency droop control is presented to the HVDC-link converter. It diminishes the frequency deviation after the disturbance in generation and load demands at the mainland system. Offshore active power \( (\Delta P_{\text{OF}}(i) \text{ where } i = t \text{ and } w \text{ represent TPG and WPG, respectively}) \) supports after adding a frequency droop control \( (R_{\text{OF}}) \) through HVDC-link converter on ORPG is expressed by (7)

\[
\Delta P_{\text{OF}} = -\Delta f_{\text{OF}}(R_{\text{OF}}(1 + sT_M)), \tag{7}
\]

where \( \Delta f_{\text{OF}} \) is the offshore frequency deviation (in Hz) and \( T_M \) is the time constant which depends on the frequency measurement device. Its value is very low and may be neglected. To take part in primary frequency control, offshore frequency \( (f_{\text{OF}}) \) depends on onshore frequency \( (f_{\text{ON}}) \) and it may be given in (8) [16]

\[
f_{\text{OF}} - f^0_{\text{OF}} = K_V K_F (f_{\text{ON}} - f^0_{\text{ON}}), \tag{8}
\]

where \( f^0_{\text{OF}} \) is the offshore nominal frequency, \( f^0_{\text{ON}} \) is mainland nominal frequency, \( K_V \) is the gain of voltage control loop of HVDC-link and \( K_F \) is the gain of frequency control loop of HVDC-link. In this work, it is assumed that both offshore and mainland system operate at the same frequency operation. Hence, the value of \( K_V, K_F \) is set to one. This makes the offshore and onshore frequency deviations proportional to each other, which enables the studied ORPG to participate in primary frequency regulation. The calculation of \( K_V \) and \( K_F \) are explained in [23] and these values are presented in Appendix 1.
3 | SYSTEM MODELLING

3.1 | System configuration

In order to explain different control strategies on WPG and TPG units connected with the mainland system through HVDC-link is shown in Figure 2. While, dynamic model of the system is shown in Figure 3. Permanent magnet synchronous generator (PMSG) is normally used in ORPG and its control strategy may be found in [8, 27]. The control strategy and model of HVDC-link are presented in [25]. It may be noted that power rating of HVDC-link is set according to the system (contains loads and CPGs) (see Figure 4). The detail of parameters of the system is presented in Appendix 1.

3.2 | Modelling of TPG

The mathematical expression of mechanical power output \( P_t \) (in MW) extracted from TPG is calculated by (9) [27]

\[
P_t = 0.5 \rho_t \pi r_t^2 V_{\text{tidal}}^3 C_{pt},
\]

where \( \rho_t \) is the water density (in kg/m³), \( r_t \) is the radius of the blades (in m), \( V_{\text{tidal}} \) is the tidal speed (in m/s) and \( C_{pt} \) is the power coefficient. \( C_{pt} \) is a non-linear function and its value ranges between 0.4 and 0.5 for modern tidal turbines. The expression of \( C_{pt} \) may be defined in (10) [6]

\[
C_{pt} = \left( \frac{e_1 e_2}{\gamma_t + e_6 \beta_t} - \frac{e_1 e_7}{\beta_t^3 + 1} - e_1 e_4 \right) \times \exp \left( \frac{-e_5}{\gamma_t + e_6 \beta_t} + \frac{e_5 e_6}{\beta_t^3 + 1} \right),
\]

where \( \gamma_t \) is the tip speed ratio, \( \beta_t \) is the blade pitch angle (in degree) and \( e_1 \) to \( e_7 \) are the constant values. \( \gamma_t \) is the ratio between the rotational speed (\( \omega_{\text{tidal}} \)) of the blades (in rad/s) at the tip of the rotor blade and \( V_{\text{tidal}} \). \( \gamma_t \) is stated by

\[
\gamma_t = \omega_{\text{tidal}} r_t / V_{\text{tidal}}.
\]

The per unit power output \( (P_{t,pu}) \) is expressed by

\[
P_{t,pu} = 0.5 \rho_t \pi r_t^2 V_{\text{tidal}}^3 C_{pt} / P_{bt} = K_f C_{pt} V_{\text{tidal}}^3
\]

\[
K_f = 0.5 \rho_t \pi r_t^2 / P_{bt}
\]

\[
\gamma_{t,pu} = \omega_t / V_t,
\]

where \( P_{bt} \) is the power output at base tidal speed (\( V_t \) (in pu)) and rotor speed (\( \omega_t \) (in pu)). \( \gamma_{t,pu} \) is the pu tip speed ratio. The
The desired electrical power output from PMSG of TPG is represented by (15)

\[ P_{\text{ref}} = xK_{\text{pt}}C_{\text{pt}} \omega^3 + P_{\text{reg}} + P_{\text{damp}}, \]  

where \( x \) is the deloaded value. The first term on the right side represents deloaded power extraction. Due to deloaded operation, TPG operates at a reduced power level instead of MPP to create power reserve margin and this uses for frequency regulation. The second term \( (P_{\text{reg}}) \) relates to power needed for frequency regulation, either by droop control or inertia control. The third term \( (P_{\text{damp}}) \) is related to damping of resonance in the double mass mechanical system. In this work, a single shaft tidal turbine is modelled, hence, the third term of (15) is ignored. At MPP operation, \( x \) becomes one and \( C_{\text{pt}} \) remains constant with pitch angle kept to zero. The variation in mechanical power output \( \Delta P_{\text{ml}} \) depends on the deviation in tidal speed \( \Delta \omega \), and \( C_{\text{pt}} \) varies with \( \beta_t \). The stability study of the system may be examined by small signal analysis. Hence, mathematical expression of deloaded TPG with linearized transfer function is derived by considering droop control and inertia control \( (K_I) \). The change in electrical power \( (\Delta P_{\text{el}}) \) with change in offshore frequency \( (\Delta f_{\text{OF}}) \) due to combined response of droop and inertia control is found as

\[ \Delta P_{\text{el}} = -(1/R_{\text{OF}} + K_e) \Delta f_{\text{OF}}, \]  

In case of TPG, \( R_{\text{OF}} \) is considered as \( R_t \). The linearized deloaded electrical power \( (\Delta P_{\text{el}}) \) in terms of small change in rotor speed \( (\Delta \omega) \) and power coefficient performance \( (\Delta C_{\text{pt}}) \) is obtained by (17)

\[ \Delta P_{\text{el}} = \frac{\partial P_{\text{el}}}{\partial \omega} \Delta \omega + \frac{\partial P_{\text{el}}}{\partial C_{\text{pt}}} \Delta C_{\text{pt}} + 3K_I x C_{\text{pt}} \omega^2 \Delta \omega, \]

\[ + K_I x C_{\text{pt}} \omega^3 \left( \frac{\partial C_{\text{pt}}}{\partial \lambda} + \frac{\partial C_{\text{pt}}}{\partial \beta_t} \right) \Delta C_{\text{pt}} \]  

Now, adding (16) and (17), the net change in electrical power \( (\Delta P_{\text{ref}}) \) in terms of \( \Delta \omega_t, \Delta C_{\text{pt}} \) and \( \Delta f_{\text{OF}} \) is expressed by (18)

\[ \Delta P_{\text{ref}} = \Delta P_{\text{el}} + \Delta P_{\text{int}} = 3K_I x C_{\text{pt}} \omega^2 \Delta \omega_t, \]

\[ + K_I x C_{\text{pt}} \omega^3 \left( \frac{\partial C_{\text{pt}}}{\partial \lambda} + \frac{\partial C_{\text{pt}}}{\partial \beta_t} \right) \Delta C_{\text{pt}} - \left(1/R_t + K_{s} \right) \Delta f_{\text{OF}} \]  

Here, droop control is implemented on TPG to participate in the primary frequency regulation and, therefore, the value of \( K_s \) is kept to zero. The variation in mechanical power output \( (\Delta P_{\text{ml}}) \) (in pu MW) of TPG depends on the deviation in tidal speed \( (\Delta V_t) \), rotor speed \( (\Delta \omega_t) \) and pitch angle \( (\Delta \beta_t) \). \( \Delta P_{\text{ml}} \) may be obtained by the following formulations (see Figure 3(a))

\[ \Delta P_{\text{ml}} = \frac{\partial P}{\partial V_t} \Delta V_t + \frac{\partial P}{\partial \omega_t} \Delta \omega_t + \frac{\partial P}{\partial \beta_t} \Delta \beta_t, \]

\[ \frac{\partial P}{\partial V_t} = 1.5 \rho \pi r_t^2 V_t^2 C_{\text{pt}}, \]

\[ -0.5 \omega_t \rho \pi r_t^2 V_t (\partial C_{\text{pt}}/\partial \gamma_t)/P_{\text{bt}} \]  

\[ \frac{\partial P}{\partial \omega_t} = 0.5 \rho \pi r_t^2 V_t^3 (\partial C_{\text{pt}}/\partial \gamma_t) (\partial \gamma_t/\partial \omega_t)/P_{\text{bt}} \]  

\[ \frac{\partial P}{\partial \beta_t} = \exp \left( -\frac{\epsilon_3}{\gamma_t + \epsilon_3 \beta_t} + \frac{\epsilon_2}{\beta_t^3 + 1} \right) \left( \frac{\epsilon_2}{\gamma_t + \epsilon_3 \beta_t} + \frac{\epsilon_2}{\beta_t^3 + 1} \right) \]

\[ - \frac{\epsilon_2}{\beta_t^3 + 1} - \epsilon_3 (\gamma_t + \epsilon_3 \beta_t)^3 \left( \frac{\epsilon_2}{\gamma_t + \epsilon_3 \beta_t} + \frac{\epsilon_2}{\beta_t^3 + 1} \right) \]  

where \( \partial C_{\text{pt}}/\partial \gamma_t \) and \( \partial C_{\text{pt}}/\partial \beta_t \) are the values of the partial derivative of \( C_{\text{pt}} \) with respect to \( \gamma_t \) and \( \beta_t \) at the specific operating point, respectively. If TPG operates at a constant pitch angle then \( \partial P/\partial \beta_t \) may be considered as zero. Similarly, when TPG operates at MPP then \( \partial P/\partial \omega_t \) is considered as zero. However, in case of droop control, \( \partial P/\partial \omega_t \) is non-zero. The power difference in terms of mechanical and electrical with inertia constant of TPG \( (i.e. M_t) \) may be expressed by (25)

\[ s \Delta \omega_t = (\Delta P_{\text{int}} - \Delta P_{\text{ref}})/M_t \]  

Putting (18) and (19) in (25), the change in electrical power output may be written in (26)

\[ \Delta P_{\text{ref}} = (\Delta V_t (a - h c) - \Delta \beta_t e f)/g - \Delta C_{\text{pt}} (1 + 1/g) (e + f) K_j x \omega_5^3 \]

\[ + \Delta f_{\text{OF}} (1/R_t + K_s) (1 + 1/g), \]  

where \( a, h, c, d, e, f, g \) are given in Appendix 2. Examination of (26) gives insight into the effect of variations in tidal speed, pitch angle, power coefficient performance and system frequency on power output of a controlled TPG. Since, the motivation of this paper is on droop control strategy and, hence, the approximation may be done by considering \( \Delta V_t \) and \( K_s \) to be zero. Therefore, (26) may be modified as

\[ \Delta P_{\text{ref}} = - \Delta \beta_t e f / g - \Delta C_{\text{pt}} (1 + 1/g) (e + f) K_j x \omega_5^3 \]

\[ + \Delta f_{\text{OF}} (1 + 1/g)/R_t. \]  

The further approximation may be done by considering \( \Delta C_{\text{pt}} \) and \( \Delta \beta_t \) to be zero for small \( \Delta f_{\text{OF}} \). The electrical power output response subject to a unit step disturbance \( (\Delta f_{\text{OF}} = \Delta f_{\text{step}}/s) \) is shown below in (28)

\[ \Delta P_{\text{ref}} = \frac{\Delta f_{\text{step}}}{s R_{\text{OF}}} (1 + 1/(M_t s - K_t)), \]
where $K_1$ is the constant parameter. Taking the inverse form for the time domain equation, the following equation is expressed in (29)

$$\Delta P_{\text{ref}}(t) = (1 + K_1(1 - e^{-tK_1/M_t}))\Delta f_{\text{step}}/R_t,$$

where $t$ is the time. From (29), it is observed that active tidal power generation output depends on different parameters such as $R_t$, $M_t$ and $\Delta f_{\text{step}}$. From (29), it is concluded that the low value of droop setting may provide high amount of active power. (29) may also be utilized to investigate the rate of change of power (i.e. ROCOP $\frac{d\Delta P_{\text{ref}}}{dt}$) of TPG and it is presented in (30)

$$d\Delta P_{\text{ref}}/dt = \Delta f_{\text{step}}K_1^2 e^{-K_1/M_t}/(R_tM_t) \tag{30}$$

$M_t$ determines amount of ROCOP in case of system unbalance conditions. Abrupt variation in power output from TPG may effect on mechanical stress and, hence, ROCOP injection is limited by the maximum value of ROCOP. The maximum value of ROCOP may be obtained from (30) at $t = 0$ in order to reduce mechanical stress on the turbine shaft. It may be calculated by (31)

$$(d\Delta P_{\text{ref}}/dt)_{t=0} = \Delta f_{\text{step}}K_1^2/(R_tM_t) \tag{31}$$

From (31), it is found that high value of $M_t$ reduces the ROCOP and it also helps to improve transient stability of the system. Few manufacturers have their own maximum ROCOP and, usually, its value may not exceed 0.45 pu/s. Parameter’s values of TPG are shown in Appendix 1 [8].

### 3.3 Modelling of WPG

The wind turbine mechanical power output ($P_w$ (in MW)) from wind speed ($V_w$) (in m/s) is described by (32) [9]

$$P_w = 0.5\rho_w\pi r_w^2 V_w^3 C_{\text{pw}}(\gamma_w, \beta_w), \tag{32}$$

where $\rho_w$ is the air density (in kg/m$^3$), $r_w$ is the radius of the blades (in m) and $C_{\text{pw}}$ is the power coefficient which is a function of tip speed ratio ($\gamma_w$) and blade pitch angle ($\beta_w$ in degree). $C_{\text{pw}}$ and $\gamma_w$ are stated by (33) and (34), respectively

$$C_{\text{pw}} = (0.44 - 0.0167\beta_w) \sin \left( \frac{\pi (\gamma_w - 2)}{15 - 0.3\beta_w} \right) - 0.00184(\gamma_w - 2)\beta_w, \tag{33}$$

where $\omega_w$ is the rotational speed of the blades (in rad/s). Similar to TPG, variation in mechanical power output ($\Delta P_{\text{mech}}$) and electrical power output ($\Delta P_{\text{ref}}$) of WPG are expressed the same as in (19) and (26), respectively. The values of parameters of WPG are shown in Appendix 1 [9].

### 3.4 PMSG

To capture optimal power from ORPG, the turbine of both TPG and WPG is coupled with PMSG. As power output from ORPG is not constant, hence, power converter is required for interfacing with the mainland system. For this, PMSG uses full-scale power converter capacity in its stator winding (since power converter is connected directly to PMSG) and may be used for a wide range of speed control capability. Therefore, PMSG improves energy conversion efficiency (i.e. mechanical to electrical) and offers wide control of real and reactive power outputs. Excitation field is provided by a permanent magnet instead of a coil and, hence, offers benefits of no winding losses, smaller size of the rotor, simple process to manufacture and high efficiency. Therefore, this work uses a PMSG based ORPG. In TPG, the equivalent inertia (i.e. $M_t$) may be calculated as sum of inertia of tidal turbine and generator. In this work, it is assumed that the rotor of turbine and the generator are connected directly. Similarly, the equivalent inertia of WPG is calculated in line with TPG. The more details of PMSG and its parameters are presented in [6].

### 3.5 AC to DC and DC to AC converters of HVDC-link

As shown in Figure 2, HVDC-link has three components and these are AC to DC converter, transmission cable and DC to AC converter. ORPG voltage is controlled by the outer voltage control loop and inner current control loop of AC to DC converter. Also, AC to DC converter may be regulated as an ideal voltage source as shown in Figure 3(b). As shown in Figure 3(c), a controller is realized for DC to AC converter to ensure power transfer from ORPGs to mainland system. DC to AC converter has two control loops. The first one is outer power loop which controls DC voltage ($V_{\text{DC}}$) and reactive power of mainland system ($\phi$) by $d$-axis current ($i_d$) and $q$-axis current ($i_q$), respectively. The reference DC voltage ($V_{\text{DC}}^*\#$) is set to a constant value so that power between offshore and mainland systems may remain same. The second one is the inner current loop. In this control loop, $d$-axis voltage ($v_d$) and $q$-axis voltage ($v_q$) are used to generate the desired AC voltage for mainland system. The more details of AC to DC and DC to AC converters are presented in [25].

### 4 SIMULATION STUDIES

In this section, simulations based experiments are carried out to analyze the performance of different control strategies used in the multi-machine power system model (see Figure 4 and Example 12.6 of [26]) comprising of CP, ORPG and HVDC-link. Offshore WPG is simulated using an aggregated model [8] with
the single rating of 300 MW and offshore TPG is simulated using an aggregated model [9] with the single rating of 300 MW. ORPGs are integrated with the studied system at bus 12. The power ratings of the HVDC-link are set to 300 MVA [25] and it is integrated between bus 12 and 13. Synchronous generators are built by a seventh order model and their rating are presented in [28]. The TPG and WPG are assumed to be functioning with 15% deloaded capacity at a tidal speed of 2.4 m/s and wind speed of 12 m/s, respectively. For both TPG and WPG, initial pitch angles are set at 30°. In this work, parameters’ value of the system is shown in Appendix 1. A step load perturbation (ΔPL) of 1% is applied on bus 7 at \( t = 2 \) s. Three cases of simulation employing different control strategies have been performed through MATLAB/SIMULINKR software. These studied cases are as follows:

The system is simulated only with CPGs,

The system is simulated with CPGs and HVDC-link,

The system is simulated with CPGs, ORPGs and HVDC-link.

The comparative response profiles of frequency deviation and ROCOFD, employing under different control strategies are displayed in Figure 5(a,b). The simulation results indicate that in Case(a), the frequency deviation has the maximum variation of -0.0188 Hz and has large settling time. In Case(b), HVDC-link with CPG decreases the ROCOFD and also reduces the maximum frequency deviation to -0.0103 Hz. In comparison to Case(a), the maximum frequency deviation becomes half. In Case(c), the available power reserve of ORPGs are injected into the power system (by droop control strategy) and this causes frequency response to further improve (maximum undershoot is found as -0.0083 Hz). As there is no inertia support from ORPGs and, hence, the value of ROCOFD for both Case(b) and Case(c) remain same (i.e. the point of the maximum frequency deviation occurs at the same time for both the cases).

From the HVDC-link point of view, DC voltage and power output variations are zero for Case(a) (see Figure 5(c,d)). Inertia control strategy from HVDC-link provides additional inertia support to the mainland system and, thus, improves transient performance of the mainland frequency deviation. The control
loop of HVDC-link allows the coupling between HVDC-link capacitors’ voltage and the mainland frequency. The dynamics of voltage and power variations of HVDC-link for Case(b) and Case(c) are presented in Figures 5(c) and 5(d), respectively. It is observed that the capacitors’ voltage decrease in response to the declining mainland frequency and capacitors discharge their energy for the system inertia support. In Case(b), HVDC-link capacitors contribute only for the system inertia without the action of droop control strategy of ORPGs. However, compared to Case(b), Case(c) provides better primary frequency response performance since the deviations in capacitors voltage and power output are low. Also, these variations may not go beyond the normal range in case of large load disturbance.

The power output variation of CPG (the combination of G1 and G2) under different cases is displayed in Figure 6(a) and power output variation of ORPGs under Case(c) is displayed in Figure 6(b). In Case(a), it is found that power output from CPG starts to rise very quickly to compensate generation and load demand gap. This is understandable that without any other frequency support (i.e. power output support from ORPGs and HVDC-link are zero), power output from CPG increases faster than Case(b) and Case(c). In Case(b), contribution from ORPGs being zero, power output from CPG increases more swiftly since additional power is transmitted to the mainland system from HVDC-link. In the case of large variation of the load, voltage deviation may even go beyond the permissible range. Therefore, in Case(c), simultaneous presence of HVDC-link and ORPGs may provide better frequency response. In this case, HVDC-link provides power output (resulting in decrease in HVDC-link voltage) to the system in reaction to the declining mainland frequency. Consequently, variation in HVDC-link capacitors voltage leads to change in offshore frequency. Hence, ORPGs increase their power output according to the falling offshore frequency. In both deloaded WPG and TPG, droop parameters and available power reserve margin are considered as same for primary frequency support. WPG provides more power output compared to TPG due to its large inertia constant (calculated from (29)). Pitch angle deviation and rotor speed variation of ORPGs are shown in Figures 6(c,d). It is found that due to large inertia of WPG, variation of pitch and speed are very low. ORPGs only improve transient performance. Thus, combined frequency control strategy (through HVDC-link and ORPGs) may provide high stability to the system in terms of reducing system frequency deviation and decreasing ROCOFD when there is unbalance between generations and load demands.

To attain a reliable operation, the maximum value of ROCOFD is required to maintain system frequency within

![Figure 6a](image1.png)  ![Figure 6b](image2.png)  ![Figure 6c](image3.png)  ![Figure 6d](image4.png)
TABLE 1  Influences of the limit of the ROCOFD

| Parameter                              | Case(a) | Case(b) | Case(c) |
|----------------------------------------|---------|---------|---------|
| Allowable load disturbance (in %)      | 3       | 3.5     | 3.5     |
| Maximum frequency dip (in Hz)          | −0.0188 | −0.0103 | −0.0083 |
| Maximum frequency dip time (in s)      | 2.5     | 2.8     | 2.8     |

permissible range at all times and this reduces the risk of tripping of under-frequency load shedding relay. The threshold value for ROCOFD response is typically set in the range between 0.1 Hz/s and 1.2 Hz/s. ROCOFD’s value may be found by the load disturbance and inertia of the studied isolated ORPGs. To study the impact of ROCOFD, the value of ROCOFD (i.e. $\delta \Delta f_{\text{DN}} / \Delta t$ at $t = 0$ s) is fixed at 0.2 Hz/s. To investigate the limit of ROCOFD in the system, allowable load disturbance, the maximum frequency deviation and the maximum frequency dip time based on the solution of (31) are shown in Table 1. It is found that allowable load disturbance and the point of maximum frequency deviation time with Case(a) is around 3% and 2.5 s, respectively. However, in Case(b) and Case(c), these values are around 3.5% and 2.8 s, respectively. These values are identical in both the cases since injected inertia (due to HVDC-link only) to mainland system are the same (as the value of $C_{\text{DC}}$ are taken same for both the studied cases). Also, time of event of the maximum frequency deviation is more for both the cases in comparison to Case(a) which proves that system inertia has raised for both the cases. In contrast, maximum frequency deviation dip occurs with Case(c) is minimum and its value is around -0.0083 Hz. This shows the active and fruitful participation of ORPGs in frequency regulation. This concludes that strategy used in Case(c) is one of the reasonable approach to improve LFC.

The impact of random load demand (modelling of system load is depicted in Figure 7(a)) is on the studied system model is analyzed to check the efficacy of different control approaches. The random load pattern is displayed in Figure 7(b) and it is applied on bus 7. The nature of different signal deviations due to random variation in load demand in above mentioned three cases are shown in Figures 8 and 9. The dynamic of frequency deviation and ROCOFD are shown in Figure 8(a,b). It is shown that Case(c) accomplishes better than other two studied cases in terms of maximum variation and settling time. Also, Case(c) configuration is successful enough in diminishing the frequency deviation to a superior level and it also improves the transient response in a much better way. HVDC voltage and HVDC active power variations under random load disturbance pattern are portrayed in Figure 8(c,d). In Case(a), the signal deviations are zero because there is no contribution from HVDC-link to mainland power system. However, Case(c) is much more companionable than Case(b). Active power output variation from CPG (combination of G1 and G2) is presented in Figure 9(a) and it suggests that the performance of Case(c) is better than other cases in terms of controlling system frequency, effectively. Also, it helps to suppress the deviation quickly after every variation in load. As shown in Figure 9(b), combined strategy (i.e. CPG (combination of G1 and G2) and ORPGs, Figure 11(a,b) shows that the high value of capacitance of HVDC-link decreases the burden on both CPG and ORPG. It helps to minimize the maximum value of power variation during the transient period.

Lastly, the frequency deviation under different capacitance values of HVDC-link is displayed in Figure 12. The value $C_{\text{DC}}$
varies between 0 mF (0 mF means no inertia support from HVDC-link) to 15 mF. It is found that high capacitance value is a feasible solution to improve the maximum frequency deviation and ROCOFD. It is clear from Figure 12 that inertia of power system increases through HVDC-link with the increase of $C_{DC}$ value and it may be possible to produce larger inertia than the inertia produced by the synchronous generator alone. Also, HVDC-link does not affect the regular operation or normal operation since its power output variation remains zero at steady-state condition.

5 | CONCLUSION

In the modern power system, it becomes a very tough task to maintain frequency deviation and ROCOFD in an
Figure 10 System dynamic response obtained under different HVDC-link capacitors. (a) frequency deviation (in Hz), (b) ROCOFD (in Hz/s), (c) HVDC voltage deviation (in pu), (d) HVDC active power deviation (in pu).

Figure 11 System dynamic response obtained under different HVDC-link capacitors. (a) active power output from CPG (in pu), (b) deviation in power output from ORPG (in pu).

Figure 12 Frequency deviation (in Hz) at different values of $C_{DC}$. This paper focuses on coordinated control approaches of ORPGs integrated into mainland power system through HVDC-link to provide fast primary frequency support as and when needed. From simulation results, it is found that HVDC-link and deloaded ORPGs (i.e. deloaded TPG and WPG) provide additional system inertia and active power support, respectively, to the mainland system which effectively improves frequency deviation as well.
as ROCOFD following load disturbance. The mainland system frequency deviation may modify the voltage of HVDC-link proportionally and provides additional inertia support to the system. Deloaded ORPGs ensure sufficient reserve generation capacity to contribute in primary frequency regulation.

Future work will focus on the analysis of long-term participation of ORPGs with HVDC-link system in frequency response similar to secondary frequency control.

**NOMENCLATURE**

- $C$: total capacitance
- $C_{\text{eq}}$: equivalent capacitance
- $C_{\text{ps}}, C_{\text{pw}}$: power coefficient of tidal, wind
- $f$: system frequency
- $f_{\text{OFF}}$: offshore frequency
- $f_{\text{ON}}$: onshore frequency
- $f_{\text{ON}}^{\text{ref}}$: mainland nominal frequency
- $H_{\text{DC}}$: inertia of HVDC-link
- $H_{\text{eq}}$: equivalent system inertia
- $H$: Inertia constant of synchronous generator
- $i_{\text{d}}, i_{\text{q}}$: d-q axis current
- $K_{\text{F}}$: frequency control loop gain of HVDC-link
- $K_{\text{V}}$: gain of voltage control loop of HVDC-link
- $M_I$: inertia of TPG
- $P_{\text{of}}$: power output at base tidal speed
- $P_{\text{damp}}$: damping of resonance in the double mass mechanical system
- $P_{\text{reg}}$: power needed for frequency regulation
- $P_I$: power output at base tidal speed
- $R_{\text{OFF}}$: frequency droop control
- $r_f, r_w$: radius of tidal blade, wind blade
- $x$: deloaded value
- $t$: time
- $T_M$: time constant of frequency measurement device
- $\delta_{\text{d}}, \delta_{\text{q}}$: d-q axis voltage
- $V_{\text{A}0}$: base value of the system
- $V_{\text{DC}}$: voltage of HVDC-link capacitors
- $V_{\text{tidal}}, V_{\text{wind}}$: Speed of tidal, wind
- $\Delta f_{\text{OFF}}$: offshore frequency deviation
- $\Delta f_{\text{on}}$: maximum allowable frequency deviation
- $\Delta P_{\text{m}}$: difference between mechanical and electrical power output
- $\Delta P_{\text{del}}$: deloaded electrical power
- $\Delta P_{\text{Di}}$: change in electrical power
- $\Delta P_{\text{me}}, \Delta P_{\text{mw}}$: variation in mechanical power output of tidal, wind
- $\Delta P_{\text{OF}}$: active power of offshore side
- $\Delta P_{\text{ON}}$: active power of onshore side
- $\Delta P_{\text{OF}, \text{ref}}, \Delta P_{\text{ON}, \text{ref}}$: variation in electrical power output of tidal, wind
- $\Delta V_{\text{DC}}$: maximum allowable voltage deviation
- $\Delta V_I$: deviation in tidal speed
- $\omega_I, \omega_w$: rotor speed of tidal, wind
- $\rho, \rho_w$: water, air density
- $\gamma_I, \gamma_w$: tip speed ratio of tidal, wind
- $\beta_I, \beta_w$: pitch angle of tidal, wind
- $\Delta \beta_I$: change in pitch angle
- $\Delta \omega_I$: change in rotor speed

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**Appendix 1**

The different parameters of TPG, WPG, HVDC-link, inertia and load are as follows:

| Model       | Parameters |
|-------------|------------|
| TPG         | Capacity: 1 MW, rated voltage = 690 V, rated rotor speed = 13 rpm, rated tidal speed = 2.4 m/s, $M_p = 0.3878 s$, $T_p = 0.2 s$, $T_{ps} = 0.08 s$, $T_s = 6 s$, $\Delta \omega_{ref} = 0$, $k_{ps} = 5$, $k_{ps} = 1$, $k_{ps} = 50$, $k_{ps} = 80$, $\epsilon_1 = 0.18$, $\epsilon_2 = 85$, $\epsilon_3 = 0.38$, $\epsilon_4 = 10.2$, $\epsilon_5 = 6.2$, $\epsilon_6 = 0.025$, $\gamma_1 = -0.043$, $R_e = 2$ Hz/pu MW, $\gamma_2 = 1027$ kg/m$^3$, $\eta = 11.5$ m, tidal speed deviation ($\Delta V_e$) = 0 |
| WPG         | Capacity: 2 MW, rated voltage = 690 V, rated rotor speed = 20 rpm, rated tidal speed = 12 m/s, $M_p = 4.5$ s, $T_p = 0.1 s$, $T_{ps} = 0.2 s$, $\Delta \omega_{ref} = 0$, $k_{ps} = 18$, $k_{ps} = 5$, $k_{ps} = 100$, $R_e = 2$ Hz/pu MW, $\gamma_2 = 1.22$ kg/m$^3$, $\eta = 58.5$ m, wind speed deviation ($\Delta V_e$) = 0 |
| HVDC-link   | $V_{DC} = 200$ kV, $\Delta V_{DC} = 20$ kV, $C_{DC} = 7500 \mu$F, $f^a = 50$ Hz, $\Delta f_e = 0.2$ Hz, $(I/T)_e = 300$ MVA, $K_{f1} = 0.04$, $K_{f2} = 25$, transformer inductance = 0.15 pu, transformer resistance = 0.005 pu, cable resistance = 0.025 $\Omega$ km $< sp > -1 < \not sp >$ cable inductance = 0.2 mH/km |

**Appendix 2**

The constants of $a$, $b$, $c$, $d$, $e$, $f$, $g$ and $K_{i1}$ are given below:

\[
\begin{align*}
 a &= 1.5 \rho \pi r_t^2 V_i^2 C_p / P_{rot}, & b &= 0.5 \omega_i \rho \pi r_t^2 V_i / P_{rot}, & \epsilon &= \partial C_p / \partial \gamma_i, \\
 d &= 0.5 \rho \pi r_t^2 V_i^3 / P_{rot}, & e &= 0.5 \rho \pi r_t^2 V_i^3 / P_{rot}, & f &= \partial C_p / \partial \beta_i, \\
 g &= M_{i1} - c d r_i / V_i + 3 K_{f1} \times C_i \omega_i^2, & K_i &= 3 K_{f1} \times C_i \omega_i^2 + c d r_i / V_i
\end{align*}
\]