ELEKTROTEHNIŠKI VESTNIK 85(4): 149-154, 2018
ORIGINAL SCIENTIFIC PAPER

A New control strategy for active-and reactive-power dispatching in a wind farm based on DFIG at no speed and power over-rating

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Abstract. The paper proposes a new strategy for wind farm to operate in three different active-and reactive-power dispatching modes without any over rating of the generator speed and power. Using the proposed modes, i.e. balance mode, maximum power point tracking (MPPT) mode and delta mode, enables the grid-operator to meet the active-and reactive-power demand. To avoid over-rating, the generators speed and power are controlled. In each operating mode, the power is controlled by electric components (DFIG rotor currents) and the speed by a pitch angle-device. In each operating mode, a new expression is proposed to calculate the stator reference active power and the generator power control. The obtained simulation results confirm the usefulness of the proposed three-mode power-dispatching control strategy.

Keywords: Wind farm control; Active and reactive power control; Balance control; Delta control; Pitch-angle control.

Krmiljenje skupine vetrnih elektrarn z uravnavanjem delovne in jalove moči in preprečevanjem preobremenitve

V prispevku smo predstavili metodo za krmiljenje skupine vetrnih elektrarn, ki delujejo v treh načinih z omejitvijo proizvedene moči in hitrosti vrtenja. S predlaganim načinom krmiljenja, ki vključuje ravnotežni način, sledenje točki največje moči in način delta, omogočamo operaterju omrežja da zadosti zahtevam po delovni in jalovi moči. Preobremenitev preprečujemo z nadzorom proizvedene moči in hitrostjo vrtenja. Pri vsakem načinu delovanja proizvedeno moč krmilimo z električnimi gradniki. Za vsak način delovanja predlagamo nov izračun moči generatorja. Rezultati simulacije potrjujejo uporabnost predlaganega načina krmiljenja.

1 INTRODUCTION

Today, there is an increasing demand for connecting large wind farms to the power network. Due to the active role of the wind farms in the grid, it is clear that large wind farms should be able to control their produced active and reactive power and to provide ancillary services, such as the grid frequency and voltage control without any over-rating. There are many papers which have studied the modelling and control of wind farms to supervise effectively the produced electricity in terms of the active-and reactive-power generation. In [1]-[2]-[3], a wind farm is controlled according to the utility manager requirements. A methodology to develop electromagnetic transient simulation models of wind farms to predict their behaviour under normal operating conditions has been presented in [4]. A particle swarm method is used to optimize the reactive power dispatch in a wind farm [5]. In [6], the authors study possibilities of a coordinated control and management of different wind farm concepts to guarantee reaching the operational set point. A supervisory control of a wind farm with a short-term wind-speed prediction is presented in [7]. In [8], the authors present a scheme for a supervisory control of a wind farm by using either an external energy-storage system or a power reserve. A storage device based on a statcom and battery storage system is presented in [9]. The main goal of the control strategy presented in [10] is to mitigate the flicker emission by a wind farm. In [11], the authors assess the contribution to the frequency control by using a variable-speed wind turbine.

Following our previous work in which we investigated the generator active and reactive power over-rating, this paper proposes a new strategy to control the active-and reactive-power of a wind farm by operating in one of the three different operating modes (i.e. balance mode, maximum power point tracking mode (MPPT) and delta mode), at no generator over-rating speed and power. Three new expressions are given to calculate the stator reference active power for the three proposed modes.

Received 15 May 2018
Accepted 9 June 2018

2 WIND-FARM CONFIGURATION

In this study, a small wind farm operating with six wind turbines is considered. Each turbine is of 1.5 MW of the nominal power. It is equipped with DFIG and variable pitch-angle device and is connected to its own terminal voltage of about 20 kV. The wind farm is connected to a 66 kV infinite bus bar as shown in Fig. 1.

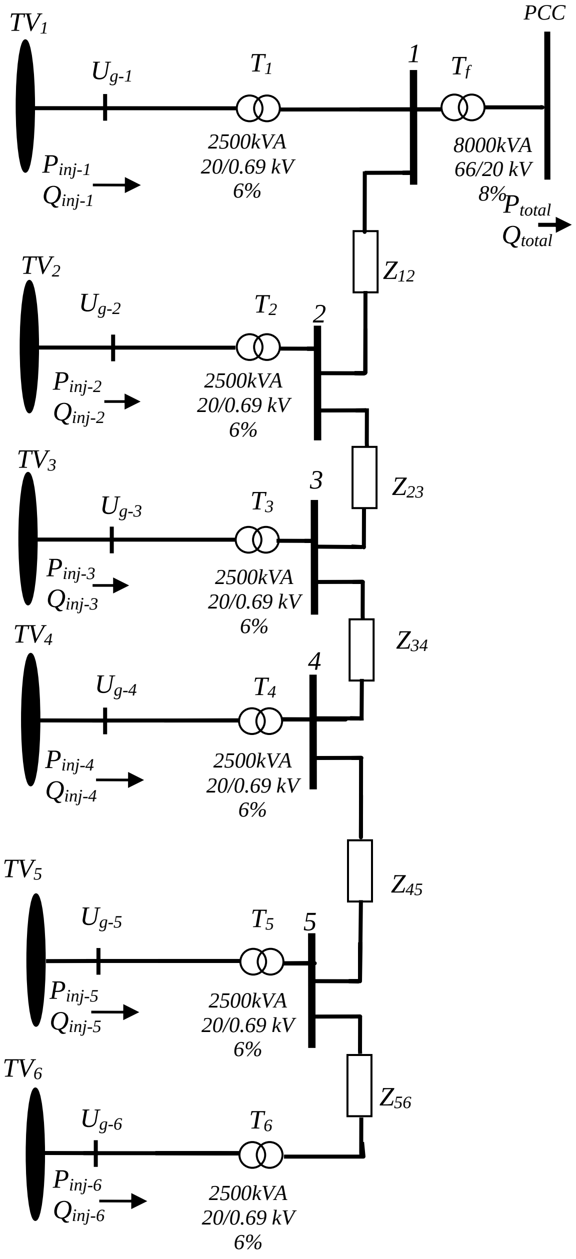

Figure1. Layout of the studied wind farm.

2.1 *Wind- system modelling*

A classical Wind-energy Conversion System (WECS) with DFIG is illustrated in Fig. 2.

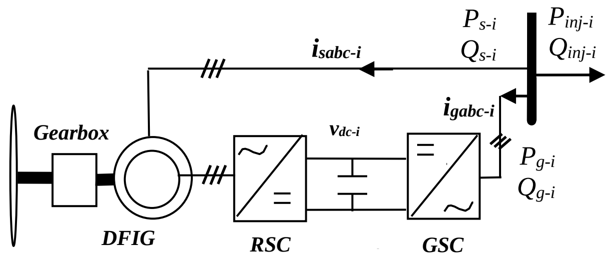

Figure2. Scheme of the i^{th} WECS of the studied wind farm.

2.1.1 *Turbine model*

The mechanical power captured by the wind turbine is given by the following classical expression [12]:

$$p_t = \frac{1}{2}\rho c_p(\lambda,\beta) s v^3 \tag{1}$$

where, ρ is the air density, s is the area of the wind wheel (m²), v is the wind speed (m/s), $cp\ (\lambda,\ \beta)$ is the turbine power coefficient, λ is the tip speed-ratio and β is the pitch angle.

The tip-speed ratio is given by the following equation:

$$\lambda = \frac{R\omega_t}{v} \tag{2}$$

where ω_t is the turbine speed (rd/s) and R is the blade radius (m).

Fig. 3 shows variations in the power coefficient versus (λ) for a constant value of pitch angle β.

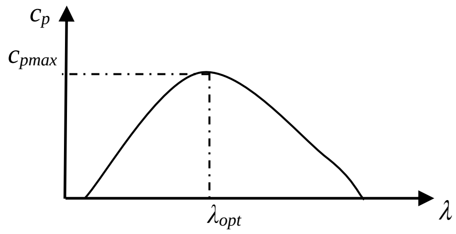

Figure 3. Power coefficient versus the tip-speed ratio.

2.1.2 *DFIG Modeling*

The DFIG voltage and flux equations, expressed in the Park reference frame, are given by [13]:

$$\begin{aligned}
u_{ds} &= R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \\
u_{qs} &= R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds} \\
u_{dr} &= R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_s - \omega_r)\psi_{qr} \\
u_{qr} &= R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_s - \omega_r)\psi_{dr}
\end{aligned} \tag{3}$$

and:

$$\begin{aligned} \psi_{ds} &= L_s i_{ds} + M i_{dr} \\ \psi_{qs} &= L_s i_{qs} + M i_{qr} \\ \psi_{dr} &= L_r i_{dr} + M i_{ds} \\ \psi_{qr} &= L_r i_{qr} + M i_{qs} \end{aligned} \tag{4}$$

The electromagnetic torque is given by:

$$T_{em} = \frac{3}{2} p \frac{M}{L_s} \left(i_{dr} \psi_{qs} - i_{qr} \psi_{ds} \right) \tag{5}$$

The stator active-and reactive-power expressions are:

$$P_s = \frac{3}{2} \left(u_{ds} i_{ds} + u_{qs} i_{qs} \right) \tag{6}$$

$$Q_s = \frac{3}{2} \left(u_{qs} i_{ds} - u_{ds} i_{qs} \right) \tag{7}$$

The WECS classical mechanical equation is:

$$T_{em} = J \frac{d\Omega_g}{dt} + f\, \Omega_g + T_L \tag{8}$$

where T_L is the aerodynamic torque of the turbine.

To establish a decoupled control of the active and reactive power, stator flux (ψ_s) is set aligned with the d axis and assumed to be constant (providing the grid is powerful and stable) [14]-[19]. Then, one can write $\psi_{ds}=\psi_s$ and $\psi_{qs}=0$. Consequently, equations (3), (4) and (5) for a steady-state regime are:

$$u_{ds} \approx 0 \tag{9.a}$$

$$u_s = u_{qs} \approx \omega_s \psi_s \tag{9.b}$$

$$\psi_s = L_s i_{ds} + M i_{dr} \tag{10.a}$$

$$0 = L_s i_{qs} + M i_{qr} \tag{10.b}$$

$$T_{em} = -\frac{3}{2} p \frac{M}{L_s} \psi_s i_{qr} \tag{11}$$

Where u_s is the stator-voltage magnitude assumed to be constant and g is the DFIG slip range.

Eqs. 9.b, 10.a and 10.b are used to rewrite the stator active and reactive power (Eqs. 6 and 7):

$$P_s = -\frac{3 u_s M}{2 L_s} i_{qr} \tag{12}$$

$$Q_s = \frac{3}{2} \frac{u_s}{L_s \omega_s} \left(u_s - M \omega_s i_{dr} \right)$$

3 ROTOR-SIDE CONVERTER CONTROL

From Eq. 12 one can see that the stator active (P_s) and reactive (Q_s) power can be controlled by acting on the rotor components (i_q and i_d). This is done by using a Fuzzy Logic Controller (FLC) seen in Fig. 4. GSC is controlled to maintain a constant DC voltage between the two converters (RSC and GSC) with a unity power factor at PCC. A more detailed control scheme of this converter is in [13].

4 DESCRIPTION OF THE PROPOSED THREE MODE POWER-DISPATCHING STRATEGY

In this section, three different control modes of the proposed power-dispatching strategy of a wind farm are discussed. For each control mode, stator reference active power (P_{sref}) is calculated as follows:

4.1 MPPT operating mode

In this mode, each of the six turbines is controlled so as to produce its maximum active power. For this purpose, the stator reference active power (P_{sref}) is determined. To determine this reference value of the MPPT operating mode, the power balance sheet is used on the basis of the WECS rotor dynamic equation. By using Eqs. 11 and 12, the following equality is easily demonstrated:

$$T_{em}\, \Omega_g = P_s (1 - g) \tag{13}$$

By replacing the electromagnetic torque using its expression (Eq .8) in Eq .13, the stator reference active power (P_{sref}) in the MPPT mode is calculated as follows:

$$P_{sref} = \frac{J \dfrac{\Omega_{gref}(kT) - \Omega_{gref}((k-1)T)}{T} \Omega_{gref}(kT) + f\, \Omega_{gref}{}^2 (kT) + P_{aerM}}{1 - g_{ref}} \tag{14}$$

where T is the sampling time; and P_{aerM} is the maximum mechanical power captured by the wind turbine in the MPPT mode:

$$P_{aerM} = \frac{1}{2} \rho c_{p\max} s v^3 \tag{15}$$

where g_{ref} is the DFIG slip in the MPPT mode. It is calculated by the following equation:

$$g_{ref} = \frac{\omega_s - p\Omega_{gref}}{\omega_s} \tag{16}$$

The generator speed reference in the MPPT mode is determined by the following equation:

$$\Omega_{gref} = \delta \frac{\lambda_{opt}}{R} v \tag{17}$$

4.2 Balance operating mode (14)

In this mode, the wind farm is controlled to meet the system operator active and reactive power (P_{wref}, Q_{wref}) demand at (PCC) (see Fig. 1). Each turbine (i) injects a constant value of the active and reactive power (P_{inj-i}, Q_{inj-i}) at its PCC (see Figs.1 and 2) in such a way that the values (P_{wref}, Q_{wref}) are satisfied. The required values (P_{inj-i}, Q_{inj-i}) of each turbine are determined by minimizing the following objective function:

$$Min \left\{ (P_{wref} - P_{total})^2 + (Q_{wref} - Q_{total})^2 \right\} \tag{18}$$

where P_{total} and Q_{total} are the total active and reactive power, respectively, produced by the wind farm at the PCC (see Fig.1).

The goal is to find P_{inj-i} and Q_{inj-i} (i=1, 2,…, 6) injected by the turbines in such a way that Eq.18 is minimized.

From Fig.2, for each turbine (i) and at its PCC, one can write the following equations:

$$P_{inj-i} = -P_{s-i}(1-g_i) \quad (19)$$

$$Q_{inj-i} = -Q_{s-i} - Q_{g-i} \quad (20)$$

where g_i is generator slip range (i); P_{s-i}, Q_{s-i} are the stator active and reactive power produced by the generator (i); Q_{g-i} is the reactive power produced from the GSC side (Q_{g-i}=0 since GSC is controlled to ensure a unity power at the grid side). Finally and after determination of (P_{inj-i} and Q_{inj-i}) (see Table1) by minimizing Eq.18, the proposed stator reference active-and reactive-power are expressed easily using Eqs.19 and 20 as follows:

$$P_{sref-i} = -\frac{P_{inj-i}}{1-g_i}) \quad (21)$$

$$Q_{sref-i} = -Q_{inj-i} \quad (22)$$

Table 1. Power dispatching results using the balance control mode.

Index of the wind turbine (*i*)	**P_{inj_i} (MW)**	**Q_{inj-i} (MVAr)**
1	0.53465	0.20124
2	0.50562	0.19533
3	0.50023	0.19702
4	0.49547	0.20907
5	0.50989	0.20644
6	0.49686	0.21545
Total	**3**	**1.5**

4.3 *Delta control mode*

In this mode, the wind farm produces less than its maximum active-power. In fact, the wind farm is controlled to produce its maximum active power with a power reserve (ΔP). Consequently, each wind turbine (i) is controlled to produce its maximum active power with a power reserve (ΔP_i) so that:

$$\Delta P = \sum_{i=1}^{i=6} \Delta P_i \quad (23)$$

The wind turbine (i) will be controlled to produce its maximum active power with a power reserve (ΔP_i). In this case, the stator reference active-power (P_{sref}) is determined by using the same expression as in the MPPT mode (Eq.14) by subtracting the power reserve (ΔP_i) as follows:

$$P_{sref} = \frac{J\,\frac{\Omega_{gref}(kT)-\Omega_{gref}((k-1)T)}{T}\,\Omega_{gref}(kT) + f\,\Omega_{gref}^{\,2}(kT) + P_{aerM} - \Delta p_i}{1-g_{ref}}$$

(24)

5 PITCH ANGLE CONTROL

The pitch angle control limits the produced power or speed. In our case, the pitch-angle control maintains the generators speeds to their nominal values, in the case of the balance and delta control. The pith angle (β) system is shown in Fig .5.

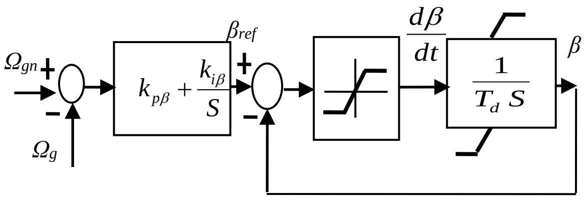

Figure 5. Pitch angle control.

6 SIMULATION RESULTS AND DISCUSSION

Three different modes are simulated to show how the proposed wind farm controller makes the wind farm power production runs according to the system-operator requirements. In the simulation, the six wind turbines are driven at different wind powers at the same mean speed value (8 m/s).

The wind turbines (*TV1* and *TV2*), (*TV3* and *TV4*) and (*TV5* and *TV6*) are driven by three different wind profiles v_{1-2}, v_{3-4} and v_{5-6} ,respectively, with a same mean value of 8m/s as shown in Fig.6.

To allow for simplicity and since the turbines responses are equal, only the simulation results obtained for the first turbine (*TV1*) are presented and discussed in detail. Figs.7, 8 and 9 show its active and reactive power (P_{inj-1} and Q_{inj-1}), its generator speed (Ω_{g1}), its power coefficient (Cp_1) and its pitch angle (β_1), respectively.

In the first period (0 *s*<t<100 *s*), the turbine runs at its maximum power. In the second period (100 s<t<200 s), the turbine injects a fixed active power (P_{inj1}=- 0.5346 MW) and a fixed reactive power (Q_{inj1}=- 0.2012 MVAr) (see Table 1 and Fig. 7). In the third and last period (200 s<t<300 s), the turbine runs with a power reserve (ΔP_1 =0.1MW) (see Fig.7). Since in the balance and reserve mode the turbine is controlled to provide less active power than its maximum, the turbine generator turbine (1) tends to accelerate. So, to avoid any over-rating, when the speed reaches its nominal value (204.2 rd/s), the pitch-angle system intervenes to limit the generator speed (Ω_{g1}) by acting on the pitch angle (β_1) and then the speed (Ω_{g1}) is maintained at its nominal value (204.2 rd/s) (see Figs .8 and 9).

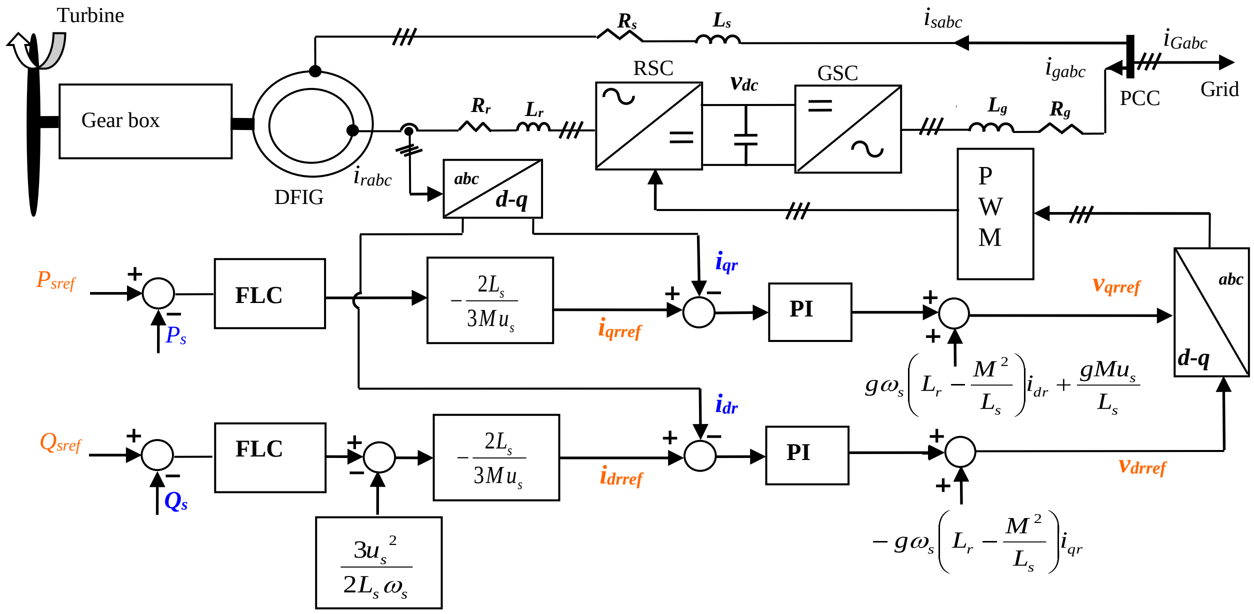

Figure 4. Control scheme of the RSC.

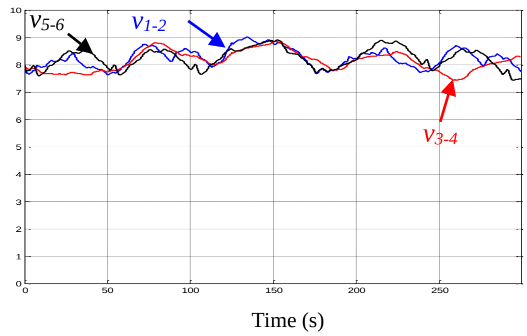

Figure 6. Wind-speed profiles applied to the farm turbines (m/s).

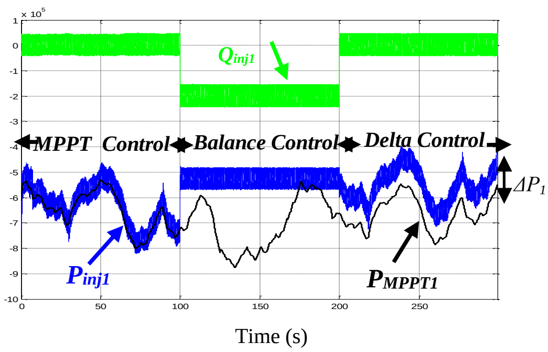

Figure 7. **TV1 turbine Powers:** Injected power (P_{inj1}), maximum power (P_{MPPT1}), power reserve (ΔP_1) (W) and injected reactive power (Q_{inj1}) (VAr).

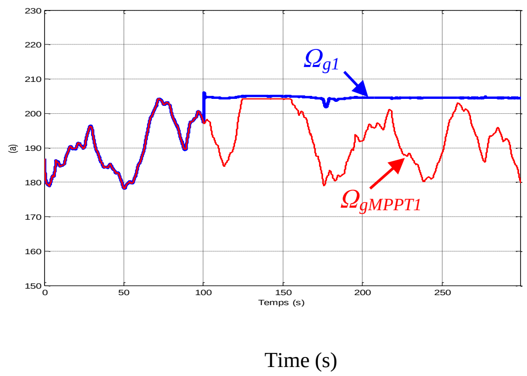

Figure 8. **TV1 turbine Speeds:** Actual generator speed (Ω_{g1}) and the reference speed at the MPPT mode (Ω_{gMPPT1}) (rd/s).

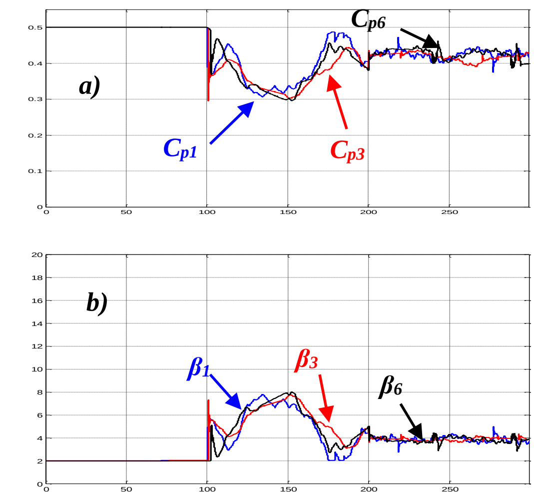

Figure 9. **Turbines TV1,TV3, TV4 Characteristics:** a) Power coefficients, b) Pitch angles (°).

Finally, from Fig.10 showing the DC link voltage for the TV1 turbine, one can see that the DC voltage (v_{dc1}) is kept practically around its reference value of 2000 V at each of the studied operating modes by controlling GSC.

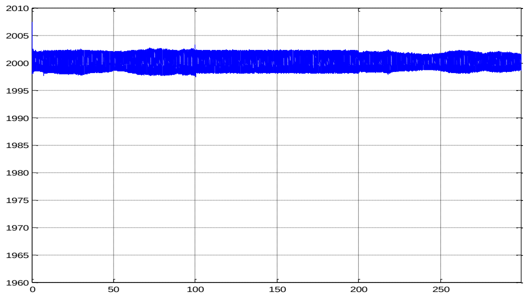

Figure10. DC link voltage (v_{dc1}) in the case of the TV1 turbine.

7 Conclusion

This paper investigates the wind farm capability to control the produced active and reactive power. A strategy of different operating modes (i.e. balance operating mode, MPPT operating mode and delta operating mode) is studied and applied to a wind farm in order to meet the grid-operator active-and reactive-power demand. Three mathematical expressions are proposed to calculate the stator reference active power for each mode. A combination of the power and control speed has permits the wind farm to operate in three different modes at no system speed and power over-rating.

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