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An open-source active power controller for grid required ancillary services

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ABSTRACT

With increasing penetration of renewable energies into modern power systems, supporting grid required ancillary services become a challenging problem. Wind turbines, as one of the main sources of renewable energies, has some inherit features which can be employed to support ancillary services for utility grids. One of the key requirements of grid operators is active power control for frequency regulation. But this requirement cannot be addressed with traditional wind turbine controllers as these controllers try to capture maximum of available power while with active power control, the output power should be limited to a predefined (time varying) set-point. Although new methods are introduced for active power control, there is no suitable comparison between them because of lack of a standards and easy to implement tools. In this paper, an extension to well-known open source reference open-source controller (ROSCO) controller based on the national renewable energy laboratory (NREL) 5 mega watt (MW) fatigue, aerodynamics, structures, and turbulence (FAST) model is proposed to support active power control. With this extension, in addition to active power control support the resulted mechanical loads on various turbine parts can be evaluated.

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1. INTRODUCTION

With increasing penetration of renewable energies into modern utility grids, supporting ancillary services by these renewable resources are mandatory. Wind turbines are one of the main sources of renewable energies and these huge structures are gradually used in place of conventional synchronous generators. Wind turbines can play a vital rule in ancillary services. For example, grid frequency can be regulated by controlling the output power of wind turbines. To this end, numerous research are conducted. For a comprehensive review on methods of frequency response of wind power plants in power systems, one can refer to [1] and references there in.

Traditional wind turbine controllers designed to extract maximum of available power from wind. But for grid support requirements, output power should be controlled to an external set-point defined by grid operator. This requirement sometimes called active power control (APC). In some configuration, this set-point maybe time varying too. So to address grid requirements, traditional wind turbine control methods should augmented with time varying set-point tracking capability. This is not an rudimentary task and the difficulties are presented in [2].

To address APC problem, several methods are suggested by researchers. Most of them, tried to modify the maximum power point tracking (MPPT) curve and forced the turbine to track a suboptimal power coefficient by employing generator torque and blade pitch angles (BPA) [3]-[8]. This method is called "de-loaded optimum power extraction curve" or simply "de-loading" or "de-rating". This method, caused higher generator speeds and so power reserve was limited to maximum of this speed [9], [10].

Frequency support from doubly fed induction generator (DFIG) wind turbines is proposed in [3]. In this scheme, frequency droop is acting on set-point of the electronic torque below its the maximum speed and is operating on the required pitch at maximum speed. The control strategy introduced in [4] for primary frequency regulation, consists of the combination of control of the static converters and pitch control, to adjust the rotor speed and the active power according to the deloaded optimum power extraction curve. Vidyanandan and Senroy [5], by continuously adjusting the droop of the generator of wind turbine, it is tried to improve the frequency response in terms of reduction in stresses on generator for low wind speeds. Developing a method based on the minimal thrust coefficient in accordance with the contour levels of aerodynamic curves is achieved in [6]. Lio *et al.* [7], instead of changing the power reference, derating is performed by modifying the rotor speed set-point. Also its effect on the turbine structural fatigue and thrust coefficient is evaluated. It is shown that derated turbines might perform better with lower rotor speed set-point if this set-point does not drive the turbine into stalled operations. The proposed control scheme in [8] based on optimization of the steady-state deloaded operating point with respect to the amount of kinetic energy stored in the rotating masses.

Wang and Tomsovic [11], an active power control framework for DFIG is proposed. In this paper, based on coordinated control strategy for inertial response control and power reserve control for primary frequency control, a control scheme is introduced to improve primary settling frequency. Nevertheless, fatigue loads are not investigated. Proportional distribution algorithm is the method which is utilized in [12]. The authors convert the APC problem to the tip-speed-ratio tracking control problem. Then, a neuro-adaptive fault-tolerant controller and a robust adaptive fault-tolerant controller based on barrier lyapunov function (BLF) are proposed. In this paper, the exerted mechanical loads of the proposed controller is not studied too.

A coordinated APC strategy is introduced in [13]. This coordinated strategy employs pitch angle control (PAC) and rotor speed control (RSC) simultaneously. It is claimed that, with simultaneous activation of PAC and RSC, full advantage of rotor kinetic energy to absorb or release extra mechanical energy can be achieved. Another coordinated APC by using PAC and RSC is proposed in [14]. It is showed that with utilizing non-zero pitch angle energy buffer of rotor inertia can be harvested to regulate output power. The method is validating both on a lab scale wind turbine simulator and national renewable energy laboratory (NREL's) fatigue, aerodynamics, structures, and turbulence (FAST). Again, this paper does not report the mechanical stresses caused by control strategy.

Lyu and Liu [15], the particle swarm optimization (PSO) algorithm is utilized for optimization problem that aims to track a dispatch command while minimizing fatigue loads. The Authors regulate the power output by means of PAC and RSC. Almost all of APC methods, to some extent, suffer from above limitation of power reserve because of generator maximum speed limit. Also, these methods differ from various aspects such as response time, overshoot, and accuracy of tracking. In addition, one the most important aspects that should be studied during APC is mechanical loads. Unfortunately, there are few researches that addressing both APC and mechanical load minimization concurrently.

Although there are numerous research on the topic of APC, evaluation and comparison of these modern controllers are very complicated. Also, open source controllers such as delft research controller (DRC) [16] and the NREL's reference open-source controller (ROSCO) [17] do not support APC by default. So, in this paper, an extension to ROSCO controller for APC is proposed to form a base for researchers to evaluate and compare their findings with a reference standard control. This paper is organized as follows: in section 2, active power control problem is introduced. Section 3, is devoted to mechanical stresses during turbines operation. In section 4, the APC support extension for ROSCO controller is proposed. Test scenario and simulation is reported in section 5, and finally conclusions are drawn in section 6.

2. ACTIVE POWER CONTROL

Following the notation used in [18] and [10], there are three main categories for APC of a wind turbine: 1-power limitation, 2-constant delta control and 3-proportional delta control. These modes are defined in brief in Table 1. In this table DR_{cmd} is de-rating command, P_n is rated power, P_r is constrained power by set-point, P_δ is the power reserve and P_{av} is the power which is generated by wind turbine in normal operation.

In power limitation mode, a limit proportional to the rated power (P_n) is set: $P_r = DR_{cmd}P_n$. However, this reserve is not controlled. In this mode, reserve power is available only if $P_{av} > P_r$. So, this mode is not referred as delta control. In constant delta control, the power reserve kept at a constant level proportional to rated power: $P_\delta = (1 - DR_{cmd})P_n$. In this mode, reserve power is available only if $P_{av} > P_r$, too. So, if there available power is less than P_r, there will be no reserve power for active power control.

Table 1. Active power control modes [10], [18]

APC methods	Power reserve	Notation
Power limitation	$max[0, P_{av} - P_r]$	$P_r = DR_{cmd}P_n$
Constant delta control	$min[P_{av}, P_\delta]$	$P_\delta = (1 - DR_{cmd})P_n$
Proportional delta control	δP_{av}	$\delta = (1 - DR_{cmd})$

Finally, in proportional delta control, power reserve is actively controlled . The power reserve in this mode is proportional to available power in normal mode (P_{av}). The set-point is defined as $\delta = (1 - DR_{cmd})$. In Figure 1, comparison of three different active power control modes is illustrated.

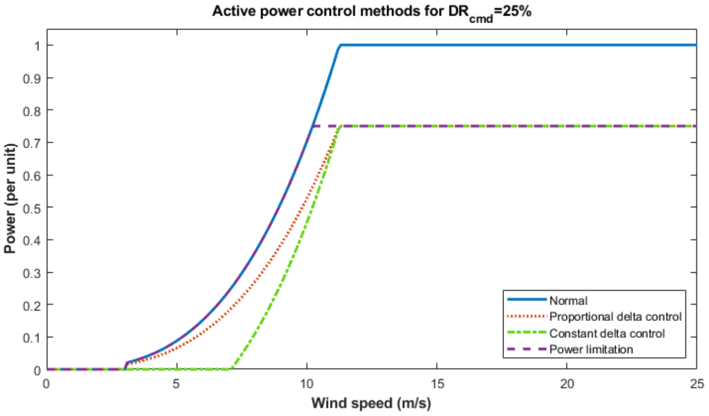

Figure 1. Different types of active power control methods

It should be noted that both the power limitation and constant delta control modes can be addressed by proportional delta control. So, in the following, the main focus will be on this mode. In the next subsection, active power control methods for wind turbines are studied in brief.

2.1. Active power control methods in wind turbines

To study active power control methods, it is required to find out the effective parameters to output power. Dynamical equation of wind turbine can be summarized as [19].

$$P_m = T_m\omega = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda, \beta) \tag{1}$$

$$J\dot{\omega} = T_m - T_c \tag{2}$$

$$\dot{T}_c = \frac{1}{\tau}T_c + \frac{1}{\tau}T_{cd} \tag{3}$$

$$\lambda = \frac{\omega R}{v} \tag{4}$$

Where P_m is the mechanical power of wind turbine, T_m is the aerodynamic torque of turbine rotor, ω is the rotor speed, ρ is the air density, R is the radius of turbine rotor, v is the wind speed, J is the inertia of turbine, T_c is the generator torque, τ is the generator time constant, λ is the tip speed ratio (TSR). Also, T_{cd} is the desired or commanded torque and β is the pitch angle which are both the control inputs of wind turbine (WT). Finally, $C_p(\lambda, \beta)$ is the power coefficient of WT which is nonlinear function of λ and β. Figure 2 shows a typical $C_p(\lambda, \beta)$ curve.

Remark: it is clear that the dynamic response of generators (electrical subsystem) in wind turbines are very faster than its mechanical subsystems. In this regard, in this study, for simplicity, mechanical power assumed to be equal to electrical power. In other words, dynamics of electrical subsystems is not considered for this study.

It can be seen in (1) that for controlling output power, one can change operating point of $C_p(\lambda, \beta)$ by means of T_{cd} (torque control) and β (blade pitch angle control). Also, there is another degree of freedom in (1): v (wind speed). Although there is no direct control to wind speed, by controlling horizontal angle between WT and wind speed, effective wind speed can be controlled. This can be accomplished by yaw angle of wind turbines. So, there are three control methods in a modern wind turbine that can be used for APC: i) yaw control, ii) torque control or rotor speed control (RSC), and iii) pitch angle control (PAC).

It should be mentioned that, yaw controllers are usually slow and cause high mechanical loads during operation. So, this controller is omitted from APC because one of the key requirements is the fast response time. So, only RSC and PAC will be considered for APC. Furthermore, torque controller is the fastest controller but their effects is limited to small amount of power control. Also, maximum generator speed limits this control scheme. In contrast, blade pitch angle controllers are slow but they have a large effect of output power. So, in a well-defined configuration, both torque and blade pitch controller should be employed concurrently: PAC for coarse tuning and RSC for fine tuning of output power. Employing both PAC and RSC for APC is generally called "coordinated APC" [13], [14].

3. MECHANICAL LOADS

The aerodynamic torque (T_a) and drag force (F_T) caused by wind power can be expressed as [20].

$$T_a = \frac{1}{2}\rho\pi R^3 \frac{C_p(\lambda,\beta)}{\lambda} v^2 \tag{5}$$

$$F_T = \frac{1}{2}\rho\pi R^2 C_T(\lambda,\beta) v^2 \tag{6}$$

Where $C_T(\lambda,\beta)$ is the thrust coefficient. This parameter is a nonlinear function of λ and β too. Figure 3 shows a typical trust coefficient curve. It should be noted that even during normal operation, there are mechanical loads exerted to tower and blade of wind turbine. Any control operation causes some extra stresses to the mechanical parts. So, evaluating mechanical loads for each controller is a mandatory task.

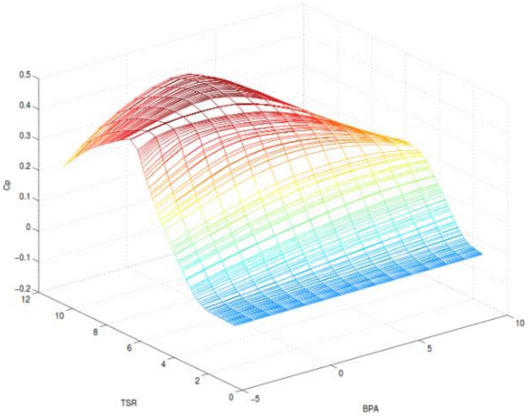

Figure 2. A typical power coefficient (Cp) curve [21]

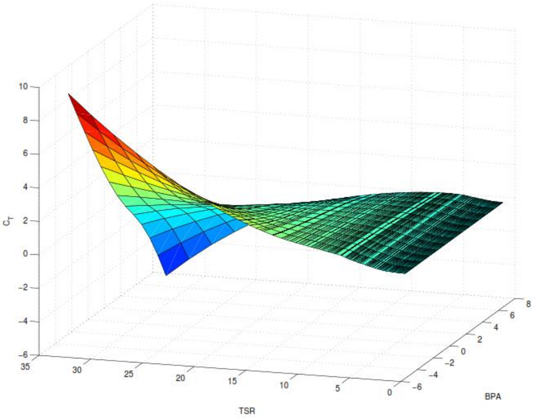

Figure 3. Thrust coefficient of a 5 mega watt (MW) wind turbine [19]

Traditional controllers did not embed mechanical loads in their calculation. Fortunately, some recent controllers address this factor e.g. [19]. However, to the knowledge of authors, limited number of literatures exist which study mechanical loads and APC, concurrently e.g. refer to [15], [22]. To this end, in this paper, the problem of APC considering mechanical effect of controllers is addressed. Fortunately, NREL's FAST wind turbine model [23], can be used as a high fidelity mechanical model of wind turbines. In this study, we have used their 5 mega watt (MW) model for mechanical loads calculations. Also, the Simulink version of well-known open-source NREL's ROSCO controller available at [24] is employed as the base controller. In the following, based on [25], the following parameters are selected for report: blade 1 edgewise moment (RootMxb1), blade 1 flapwise moment (RootMyb1), tower side-to-side moment (TwrBsMxt), tower base fore-aft moment (TwrBsMyt). Also, rotor azimuth angular speed (LSSTipVxa) is reported.

4. AN EXTENSION TO ROSCO CONTROLLER FOR ACTIVE POWER CONTROL

In this section, an extension for APC support is proposed for well-known open source ROSCO controller which is available at [17]. It should be noted that Simulink version of this controller is employed in this study. As mentioned earlier, a reasonable active power controller should employ RSC and PAC concurrently. To this end, dependent to the wind speed, new set-points for both rotor speed (for controlling torque) and blade pitch angle should be defined for power delta control command. In this research 2-dimentional lookup tables are employed to define set-points for delta power control. The first dimension is the wind speed and the second dimension is the delta power set-point (dp). This method is also suggested in [10] but with different parameters. Details of ROSCO controller and the theory behind it can be found at [26]. In this research, for augmenting ROSCO controller with APC support, three controllable parameters are defined. The label of these parameters is selected based on ROSCO notation. Original ROSCO parameters should be replaced with these new parameters.

a. VS_TSRopt_dp is the output of RSC or torque controller lookup table which will be used in torque controller module, VS_TSRopt in original ROSCO model should be replaced by VS_TSRopt_dp.
b. VS_RtTq_dp is the output of Rated torque lookup table. This parameter is the modified version of rated torque variable which is used in RSC or torque controller module. VS_RtTq in original ROSCO model should be replaced by VS_RtTq_dp.
c. $beta\_dp$ is the output of blade pitch angle lookup table. This parameter is employed in PAC or blade pitch angle controller. This parameter should be added to minimum pitch angle block in ROSCO blade pitch saturation block. The block diagram of the proposed controller is depicted in Figure 4.

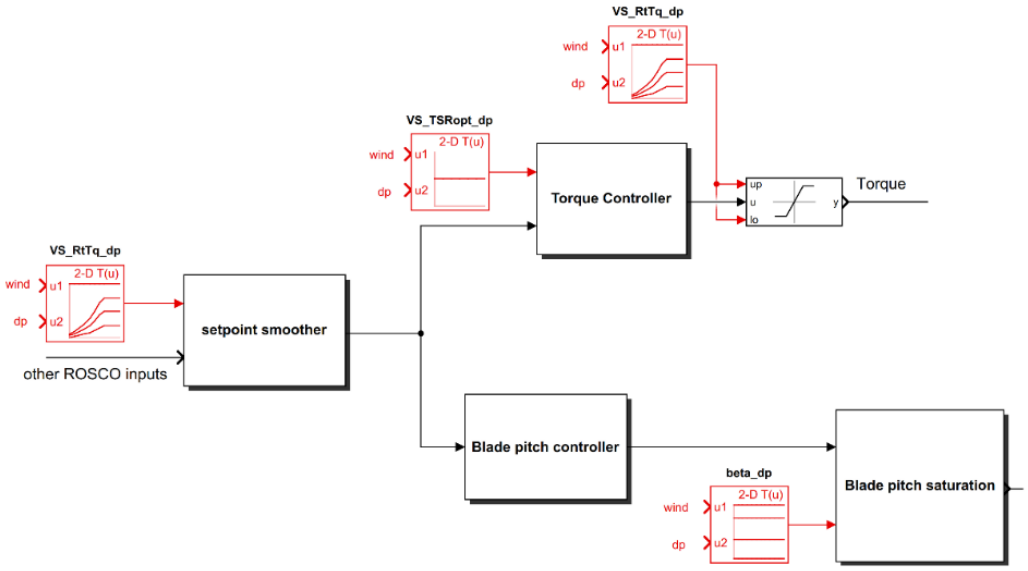

Figure 4. Block duagram of proposed contoller extension to ROSCO controller is shown in red

5. TEST SCENARIO

In this study, for evaluating mechanical loads during APC, a stepped wind speed profile is selected. This profile spans wind speed from 5 m/s to 15 m/s with 1 m/s steps in each 90 s and covers both below rated and above rated operating regions of NREL's 5 MW wind turbine. Figure 5, shows the wind speed profile. This parameter is called wind speed in x direction (Wind1VelX) in FAST's notation.

Also, four set-points for APC is defined: 0%, 25%, 50%, and 75% of nominal power. If one selects $dp = 25\%$ of nominal power as set-point, it means only 75% of nominal power should be harvested of wind turbine. In the FAST notation, generator power (GenPwr), generator torque (GenTq) and blade 1 pitch (Blpitch1) angles are reported for comparison.

In the following, red, green, blue and black colors are used for 0, 25, 50, and 75% respectively. For the NREL's 5 MW wind turbine model, simulation is conducted and the following tables summarize the results at steady state conditions. Table 2 depicts the output power of wind turbine for different set-point and for selected wind speed profile. It is clear that the proposed extension to the ROSCO controller works well.

Table 2. APC with different set-points for selected wind speed profile

		Output power (KW)										
Wind speed		5	6	7	8	9	10	11	12	13	14	15
Dp (%)	0	400	740	1174	1741	2471	3377	4316	5000	5000	5000	5000
	0.25	318	567	917	1345	1903	2570	3246	3750	3750	3750	3750
	0.5	205	342	580	840	1243	1700	2200	2500	2500	2500	2500
	0.75	99	173	282	406	573	790	1101	1250	1250	1250	1250

It can be concluded that the proposed methods are perfect for above rated wind speed (region 3) in which maximum power of a turbine is achieved. Nevertheless, in region 2 (below rated wind speed) there were some inaccuracies especially in low wind speeds. The reason of this inaccuracy could be stemmed in the lack of effectiveness of RSC and PAC as there were insufficient aerodynamic torques because of by low wind speed. Based on Figure 2 and Figure 3, it is clear that aerodynamic torques are declined in low wind speeds.

Simulation outputs are reported in the following figures: Figure 6 illustrate the blade 1 pitch angle, Figure 7 depicts the generator power, and Figure 8 shows the generator torque for selected wind speed profile. For ease of comparison, these parameters for different delta power setpoints are reported in the same figure. As mentioned earlier, every controller has some extra loads on mechanical parts of a wind turbine. So, in this section, mechanical loads caused by proposed controller is investigated. It should be noted that the proposed controller in this paper is based on ROSCO controller and the only difference is the set-points for APC which are defined by external commands through three lookup tables. Based on [25], the following signals are selected as mechanical related loads: blade 1 edge-wise moment (RootMxb1), blade 1 flap-wise moment (RootMyb1), tower side-to-side moment (TwrBsMxt), tower base fore-aft moment (TwrBsMyt). Figure 9 to Figure 12, illustrate mechanical loads caused by APC controller for different set-points.

From Figure 9 to Figure 12 it can be concluded that with increasing dp, all mechanical loads exerted on blades and tower are reduced. It seems, the reason for this effect is stemmed in blade pitch angle. Based on (5) to (6) and Figure 3, increasing blade pitch angle can reduce mechanical stresses with decreasing C_P and C_T values. Also from these results, as expected, it can be inferred that PAC has higher impact on APC than RSC. As expected, due to wind speed vector (wind direction), flap-wise and fore-aft moments are higher than edge-wise and side to side moments for blade and tower structures respectively. So as is predicted, different dp set-points for PAC causes higher differences on flap-wise moments than edge-wise for blades and higher fore-aft moments than side-to-side ones for tower base. Although, these moments are increasing with wind speed; activation of PAC make them declining. Once more, it can be concluded that PAC has higher impact on APC than RSC.

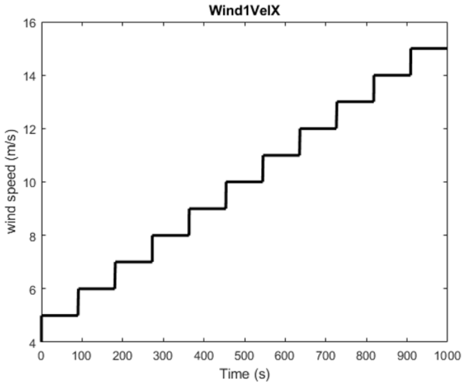

Figure 5. Wind speed profile

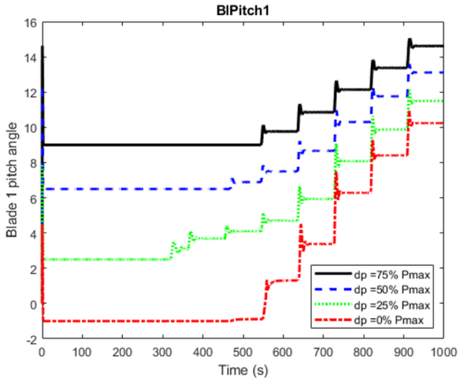

Figure 6. Blade 1 pitch changes for different power set-point

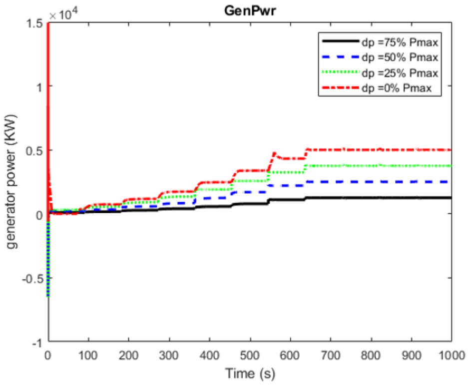

Figure 7. Generator power changes for different power set-points

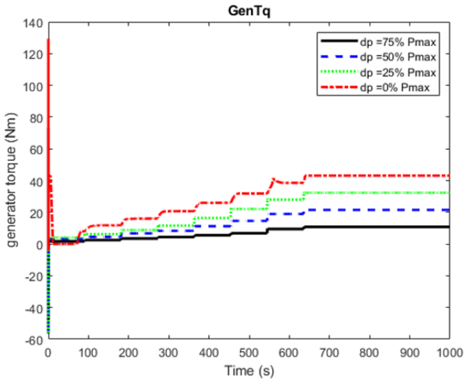

Figure 8. Generator torque changes for different power set-points

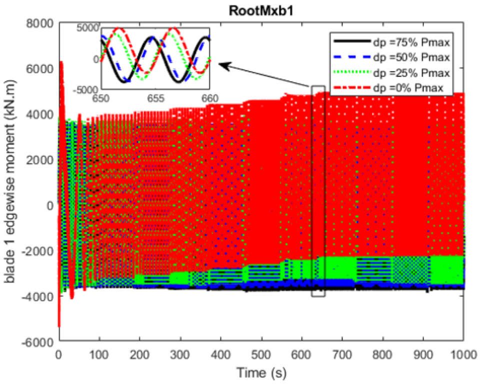

Figure 9. Blade 1 edge-wise moment for different power set-points

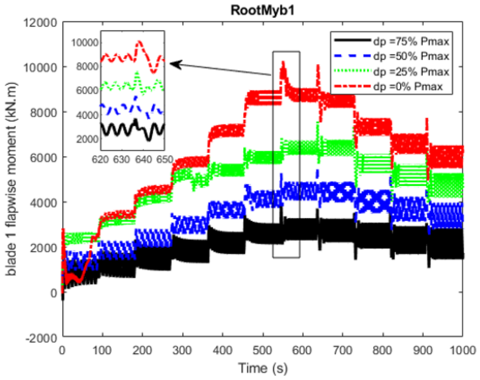

Figure 10. Blade 1 flap-wise moment for different power set-points

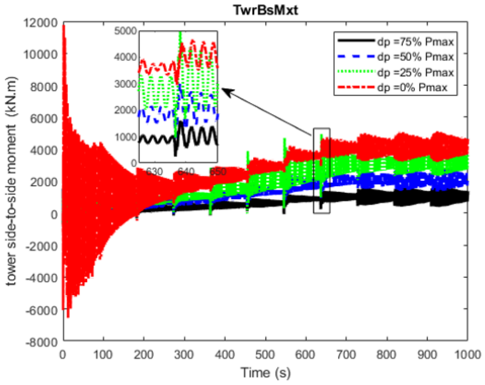

Figure 11. Tower base side to side moment for different power set-points

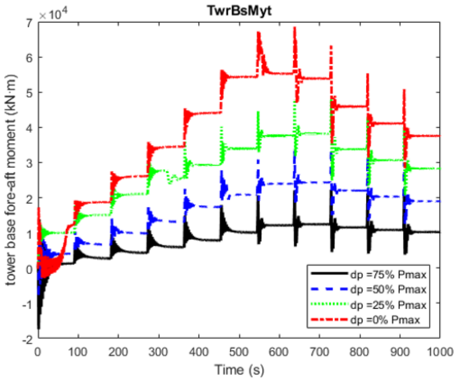

Figure 12. Tower base fore-aft moment for different power set-points

6. CONCLUSION

In this paper, an extension to well-known open-source NREL's ROSCO wind turbine controller for active power control support is introduced. The proposed controller employs rotor speed and pitch angle controllers simultaneously to achieve power set-point tracking which is a key requirement for modern utility grids. In total, three lookup tables are employed to achieve this task. Also, mechanical loads exerted by controller are evaluated. The proposed controller can serve a basis for researchers to compare and evaluate their finding in the context of active power control of wind turbines. The future trend of research in active power control could be improving accuracy of set-point tracking and enhancing the speed of transient response of the overall system. Fortunately, this trend could be well addressed by the proposed controller by means of some minor modification to the look-up tables.

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