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Barradas Berglind, Jose de Jesus; Jayawardhana, Bayu; Wisniewski, Rafał

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Wind Turbine Control with Active Damage Reduction through Energy Dissipation

J.J. Barradas-Berglind[1,2], Bayu Jayawardhana[2] and Rafael Wisniewski[1]

Abstract— In this paper we propose an active damage reduction control strategy for wind turbines based on dissipated energy. To this end we rely on the equivalences relating both damage in the rainflow counting sense and dissipated energy to the variations of Preisach hysteresis operators. Since dissipation theory is well suited for control systems, we adopt the dissipated energy of a Duhem hysteresis model that is described by a differential equation. Accordingly, we incorporate the dissipated energy into the optimal control problem formulation as a proxy to the damage. Lastly, the proposed strategy is evaluated with NREL's FAST high-fidelity non-linear wind turbine.

I. INTRODUCTION

Fatigue damage is considered as a critical factor in structures where it is necessary to ensure a certain life span under normal operating conditions, especially in turbulent or harsh environments. These environmental conditions lead to irregular loadings, which decrease the life expectancy of structures or materials exposed to them. This is the case for wind turbines, and structures in contact with waves and uneven roads, among other examples. Fatigue is a phenomenon that occurs in a microscopic scale, manifesting itself as damage [1]. The most popular and widely used measure of fatigue damage is the so-called rainflow counting (RFC) method, whose name comes from an analogy with roofs collecting rainwater [2].

Motivation. Despite its widespread usage [3], the RFC method has a complex non-linear algorithmic character, which mainly limits its application as a post-processing tool. Nevertheless, the RFC method has a physical connection to the damaging process, where its purpose is to identify the closed hysteresis loops in stress and strain signals [4]. Particularly, in [5] an equivalence between symmetric RFC and a particular hysteresis operator is provided, allowing to incorporate a fatigue estimator online within the control loop, in contrast to the RFC case. However, the inclusion of hysteretic elements in control loops is not straightforward, since hysteresis operators involve discontinuities and non-smooth non-linearities, and in the case of the Preisach hysteresis model, infinite dimensional memory [6].

Related work. In the present paper we propose an active damage reduction control strategy for wind turbines based on the dissipation of a hysteresis operator. We propose a model predictive control (MPC) based strategy that incorporates the dissipated energy as a proxy for damage in the cost functional. In [7], the notion of dissipated energy as lifetime parameter was suggested, and in [5], [6] both the total dissipated energy and the accumulated damage in the rainflow counting sense are equated to the total variations of certain hysteresis operator. Optimal control problems with Preisach hysteresis have been investigated in works such as [8]–[10]. However, it is not straightforward to include the Preisach hysteresis into the optimal control problem, due to the lack of computational tractability of this infinite-dimensional operator. Hence, we adopt the Duhem hysteresis framework, where the dissipated energy in the Duhem model [11], [12] is used as a measure or proxy for accumulated damage. The previous can be achieved since the Duhem model can be explicitly written as a differential equation [13], [14], thus facilitating its inclusion in the optimal control problem. Due to the mixed nature of the wind turbine control objectives [15], [16], i.e., power extraction maximization and mechanical load alleviation, several optimization-based control strategies have been proposed in the literature, e.g., [17]–[19]. In [20], control strategies were designed by approximating fatigue load with an analytical function based on spectral moments.

Contribution. In this paper we adopt the notion of damage as studied in [6] to the Duhem hysteresis model. Accordingly, we include the dissipated energy in the cost functional of a MPC problem, where it serves as a measure of the damage in a specific component. The main advantage of the proposed damage reduction strategy is that control of complex physical systems can be realized since the Duhem model can be explicitly written as a differential equation. Lastly, we illustrate the proposed control strategy through wind turbine simulations on NREL's FAST 5MW wind turbine [21]. Moreover, this damage estimation and control methodology can be extended to different application domains, ranging from magnetics to mechanics due to the diversity of the models that can be described in the Duhem framework [12].

Outline. The remainder of the paper is organized as follows: In Section II we present key definitions of dissipative systems and the energy dissipation in the Duhem hysteresis model; furthermore, we elaborate on the connection between dissipated energy and damage. Subsequently, in Section III the wind turbine model for controller synthesis is presented. Accordingly, in Section IV we use the dissipated energy of the Duhem model as a proxy to damage in a predictive control problem formulation, which we illustrate via simulation results with NREL's FAST non-linear wind turbine. Lastly, conclusions are given in Section V.

[1]Department of Electronic Systems, Aalborg University, Aalborg East 9220, Denmark `raf@es.aau.dk`.

[2]Engineering and Technology Institute Groningen, Faculty of Mathematics and Natural Sciences. University of Groningen, Nijenborgh 4, 9747AG Groningen, The Netherlands {`j.d.j.barradas.berglind,b.jayawardhana`}`@rug.nl`.

II. Energy Dissipation

In this Section we introduce the notion of dissipative systems, we elaborate on the connection between energy dissipation and accumulated damage and present the dissipation properties of the Duhem hysteresis model that we use in the control strategy formulation.

For two open sets $X \subset \mathbb{R}^n$ and $Y \subset \mathbb{R}^m$ we denote $\mathcal{C}^1(X, Y)$ as the space of continuously differentiable functions $f : X \to Y$; if $Y = \mathbb{R}$ we use the notation $\mathcal{C}^1(X) := \mathcal{C}^1(X, \mathbb{R})$. Furthermore, we denote $AC(X)$ as the space of absolutely continuous functions $f : X \to \mathbb{R}$.

A. Dissipative Systems

Consider the non-linear system

$$\dot{x} = f(x, z), \tag{1a}$$
$$y = h(x, z), \tag{1b}$$

where $f \in \mathcal{C}^1(\mathbb{R}^n \times \mathbb{R}, \mathbb{R}^n)$ and $h \in \mathcal{C}^1(\mathbb{R}^m \times \mathbb{R}, \mathbb{R}^m)$ for bounded input z. Following [22], the notion of a dissipative system involves: (I) a dynamical system such as (1), (II) a supply rate $S : AC(\mathbb{R}) \times AC(\mathbb{R}) \to AC(\mathbb{R})$, and (III) a storage function $H : \mathbb{R}^n \to \mathbb{R}$.

Definition 1 (Dissipation inequiality): The system (1) is said to satisfy the dissipation inequality with respect to the supply rate S and the storage H if

$$H\big(x(t_2)\big) - H\big(x(t_1)\big) \leq \int_{t_1}^{t_2} S\big(z(t), y(t)\big)\, dt \tag{2}$$

holds for all t_1, $t_2 \in \mathbb{R}$, with $t_2 \geq t_1$.

Definition 2 (Dissipative system): The system (1) is said to be dissipative with respect to the supply rate S if there exists a non-negative storage H such that the dissipation inequality (2) holds. If (2) holds with equality, then (1) is lossless with respect to S.

In broad terms what Definition 2 entails is that when a system is dissipative, the stored energy is somewhat less that the energy supplied. Thus, some energy is lost or dissipated in the process.

B. Energy Dissipation and Damage

Letting $\mathcal{D}$ be the dissipated energy, in the context of stress-strain relationships the second law of thermodynamics states that one can obtain the energy dissipation rate as

$$\dot{\mathcal{D}} = \dot{\epsilon}\sigma - \dot{V}, \quad \dot{\mathcal{D}} \geq 0, \tag{3}$$

where ϵ is strain, σ is stress, and V corresponds to internal energy. Considering a Preisach hysteresis operator $\mathcal{W}$ one can write a constitutive law as

$$\epsilon = \mathcal{W}[\sigma]. \tag{4}$$

In [5], [6] it is shown that both the total dissipated energy and the accumulated damage in the rainflow counting (RFC) sense are equal to the total variations of certain Preisach hysteresis operator. The RFC method is based on an algorithm that extrapolates information from extrema, i.e., maxima and minima, of a time series followed by the Palmgren-Miner

rule of damage accumulation [3], [4]. In [23], [24] wind turbine control strategies were developed based on fatigue damage estimation relaying on the equivalence between RFC and the variation of a hysteresis operator.

Based on the previous relationships, in this paper we assume that the accumulated damage is proportional to the amount of dissipated energy. Furthermore, we lean on dissipation theory since it is well developed and studied. Accordingly, we incorporate the dissipated energy of a different hysteresis operator, i.e., the Duhem operator, which has the advantage of being represented by a differential equation instead of the Preisach hysteresis operator. Therefore, in the next Section we characterize the dissipation $\mathcal{D}$ by means of a Duhem hysteresis operator.

C. Dissipation in the Duhem Hysteresis Model

The Duhem hysteresis model can be explicitly written as a differential equation, and focuses on the fact that the output can only change its character when the input changes direction [14]. Consequently, the Duhem model has scalar memory, i.e., it accesses information about past evolution through a single variable at each time, in contrast to the Preisach model that exhibits infinite dimensional memory [6]. Using the same description as in [12]–[14] the Duhem operator $\Phi : AC(\mathbb{R}_+) \times \mathbb{R}_+ \to AC(\mathbb{R}_+), (z, y_0) \mapsto \Phi(z, y_0) =: y$ is described by

$$\dot{y}(t) = f_1\big(y(t), z(t)\big)\dot{z}_+(t) + f_2\big(y(t), z(t)\big)\dot{z}_-(t), \tag{5a}$$
$$y(0) = y_0, \tag{5b}$$

where $\dot{z}_+(t) := \max\{0, \dot{z}(t)\}$, $\dot{z}_-(t) := \min\{0, \dot{z}(t)\}$ and $f_1, f_2 \in \mathcal{C}^1(\mathbb{R}^2)$. The existence of solutions to (5) has been addressed in [14].

As discussed in [11], the hysteretic phenomenon can be classified according to its input-output mapping into counter-clockwise (CCW), clockwise (CW) or more complex behavior. In the case of Preisach hysteresis in [6, p.66] it is explained that whether this input-output behavior is CW or CCW, depends on the choice of the input variable. According to [6], the constitutive law in (4) gives rise to CCW loops. Hence, since we are interested in such relationships we will consider the CCW case in the Duhem model in the sequel.

Definition 3 (Duhem model CCW dissipativity inequality): The Duhem operator as in (5) is said to be dissipative with respect to the supply rate $S(z, y) = \dot{y}z$ if there exists a non-negative function $H : \mathbb{R}^2 \to \mathbb{R}_+$ such that for every $z \in AC(\mathbb{R}_+)$ and $y_0 \in \mathbb{R}$

$$\frac{dH(y(t), z(t))}{dt} \leq \dot{y}(t)z(t) \tag{6}$$

holds for almost all $t \in \mathbb{R}_+$ with $y := \Phi(z, y_0)$.

If we consider H as defined in Definition 3 as being the stored energy in the system, the inequality (6) can be interpreted as the exchange of energy with the environment where the supplied energy given by $\int_0^T \dot{y}(\tau)z(\tau)d\tau$ is subtracted by a non-negative quantity, which we refer to as the *dissipated energy*. Examples on how to construct H can be found in [25].

Definition 4 (Duhem CCW Dissipated energy): For the Duhem hysteresis model Φ with $y = \Phi(z)$, the dissipated energy $\mathcal{D} : AC(\mathbb{R}_+) \times AC(\mathbb{R}_+) \to AC(\mathbb{R}_+)$ for the CCW case is defined by

$$\mathcal{D}(y,z) = \int_0^T \dot{y}(t)z(t)dt - H\big(y(T),z(T)\big) + H\big(y(0),z(0)\big). \tag{7}$$

It is immediate to check that $\mathcal{D}(y,z) \geq 0$ and $\dot{\mathcal{D}}(y,z) \geq 0$ for all t, or in other words the dissipated energy is a non-decreasing function along the trajectory of y and z.

Notice the relationship of this property to the dissipated energy of the Preisach model, and consequently to damage in the rainflow counting sense as discussed before.

D. Semi-linear Duhem Hysteresis

As mentioned before, the Duhem model can be explicitly written down as a differential equation. In this paper, we consider the Duhem semi-linear model [26], where the Duhem operator $y = \Phi(z)$ is governed by

$$\dot{y} = (\bar{\kappa}_1 y + \bar{\mu}_1 z)\,\dot{z}_+ + (\bar{\kappa}_2 y + \bar{\mu}_2 z)\,\dot{z}_-, \tag{8}$$

with $\dot{z}_+ := \max\{0, \dot{z}\}$, $\dot{z}_- := \min\{0, \dot{z}\}$, and $\bar{\kappa}_1, \bar{\kappa}_2, \bar{\mu}_1, \bar{\mu}_2$ being parameters that characterize the stress-strain behavior. The semi-linear Duhem hysteresis model in (8) can also be expressed as the switched system

$$\dot{y} = \begin{cases} (\bar{\kappa}_1 y + \bar{\mu}_1 z)\,\dot{z}, & \text{if } \dot{z} \geq 0, \\ (\bar{\kappa}_2 y + \bar{\mu}_2 z)\,\dot{z}, & \text{if } \dot{z} \leq 0. \end{cases} \tag{9}$$

Using the Euler approximation the differential equation in (9) can be discretized using a sampling time T_s as

$$y_{k+1} - y_k = \begin{cases} (\kappa_1 y_k + \mu_1 z_k)\,z_{k+1} - z_k, & \text{if } z_{k+1} - z_k \geq 0, \\ (\kappa_2 y_k + \mu_2 z_k)\,z_{k+1} - z_k, & \text{if } z_{k+1} - z_k \leq 0, \end{cases} \tag{10}$$

with $\kappa_1 = \bar{\kappa}_1 T_s$, $\mu_1 = \bar{\mu}_1 T_s$, $\kappa_2 = \bar{\kappa}_2 T_s$ and $\mu_2 = \bar{\mu}_2 T_s$.

III. WIND TURBINE MODEL

The wind turbine plant model to be controlled is the standard NREL 5MW wind turbine [21], which is described in the following Section.

A. Wind Turbine Dynamics

Parting from the rotor disc approach the tip speed ratio is a rational function defined as $\lambda(\omega_r, v) := R_r \omega_r / v$, where R_r is the rotor radius, ω_r is the rotor angular speed and v corresponds to the effective wind speed at the rotor. In wind turbine aerodynamics two of the most important quantities are the extracted mechanical power by the rotor

$$P_r(\lambda, \beta_p) = \frac{\pi}{2}\rho_a R_r^2 v^3 C_P(\lambda, \beta_p), \tag{11}$$

and the rotor thrust force

$$F_t(\lambda, \beta_p) = \frac{\pi}{2}\rho_a R_r^2 v^2 C_T(\lambda, \beta_p), \tag{12}$$

where C_P represents the aerodynamic efficiency and C_T represents the thrust coefficient, both in terms of the collective blade pitch angle β_p and the tip speed ratio λ. Furthermore, ρ_a stands for the air density.

The thrust force $F_t(\lambda, \beta_p)$ is transferred to the tower top through the nacelle, resulting in tower fore-aft motion. It is possible to simplify the tower fore-aft dynamics by the second order differential equation

$$M_t \ddot{y} + B_t \dot{y} + K_t y = F_t, \tag{13}$$

with y being the tower top displacement and M_t, B_t, and K_t being the identified mass, damping, and stiffness of the model.

For controller design we consider the rotational mode of the shaft, described by the following set of differential equations

$$J_r \dot{\omega}_r = T_r(\lambda, \beta_p) - K_\theta \theta - B_\theta \dot{\theta}, \tag{14a}$$

$$J_g \dot{\omega}_g = -T_g + \frac{K_\theta}{N_g}\theta + \frac{B_\theta}{N_g}\dot{\theta}, \tag{14b}$$

$$\dot{\theta} = \omega_r - \frac{\omega_g}{N_g}, \tag{14c}$$

where ω_r corresponds to the rotor angular velocity, ω_g to the generator angular velocity, and θ to the shaft torsion. Furthermore, N_g stands for the gear ratio, T_g is the generator torque and $T_r(\lambda, \beta_p) = P_r(\lambda, \beta_p)/\omega_r$ is the aerodynamic rotor torque. This model assumes that the gearbox is perfectly stiff, while transferring deformations on a low-speed shaft. The low-speed shaft is modeled by a rotational moment of inertia, and a viscously damped rotational spring. The rotor and shaft inertia are captured by the inertia J_r. The drive-train stiffness and damping are combined into one spring and one damper on the rotor side with coefficients K_θ and B_θ, respectively. This model is sketched in Fig. 1.
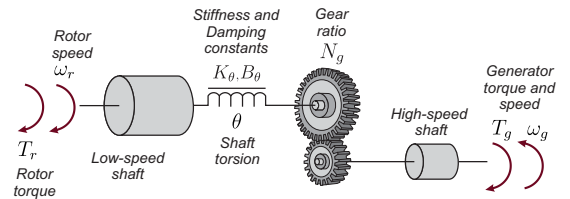

Fig. 1. Wind turbine drive-train model.

B. Linearized and Discretized Plant Dynamics

Linearizing and discretizing with a chosen sampling time T_s the model in (14) around an operating point for a chosen mean wind speed, the following DLTI system is obtained

$$x_{k+1} = A_d x_k + B_d u_k + E_d d_k, \tag{15}$$

where the state vector is given by $x_k = (\omega_{g,k}, \omega_{r,k}, \theta_k)$, and the vector of inputs or controls is given as $u_k = (\beta_{p,k}, T_{g,k})$. Lastly, the residual of the wind speed is considered as an unknown disturbance such that $d_k = v_k$. The system parameters from (14) are taken from [21] after linearizing around an operating point.

Furthermore, we use the state selector C such that

$$z_k = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} x_k = C x_k = \theta_k, \tag{16}$$

is the input to the Duhem hysteresis model in (10). Hence, we see the shaft torsion θ as the stress input σ to (4). In the sequel we use the dissipated energy of this Duhem model as a proxy of the damage in the shaft.

C. Drive-train damper

Since we are interested in assessing the damage in the shaft, it is relevant to remove the oscillations in the shaft torsion signal caused by the drive-train resonance. Accordingly, to add damping to the drive-train we use the filter

$$G \frac{2\xi\omega_d(1+\tau s)}{s^2 + 2\xi\omega_d s + \omega_d^2}, \tag{17}$$

where ω_d is the drive-train frequency to be damped, ξ is the damping factor, τ can be used to compensate for lags, and G is the gain of the filter [16].

IV. ACTIVE DAMAGE REDUCTION CONTROL STRATEGY

Model predictive control (MPC) is an optimization based control strategy that handles both complex systems and constraints; the idea behind MPC is to predict the state evolution since the system dynamics are known and effectively solves a constrained optimal control problem. The solution to this problem yields an optimal sequence of inputs, from which only the first one is implemented and the rest is discarded, also known as implemented in receding horizon fashion. This procedure is repeated in the successive time steps [27], [28].

In this Section we present a modified MPC based strategy where we include the dissipated energy in the cost functional, as a means to penalize the damage in the shaft.

A. Cost Functional Definition

Several damage reduction MPC based strategies for wind turbine control have been proposed, for example in [17], [23], [24]. The intention here is to make use of the dissipated energy in (7) as a measure or proxy for accumulated damage. We use the observation that z and y are bounded and H is continuous, hence for sufficiently large time T the primary contribution in dissipation is due to the supply rate S and thereby we can approximate (7) by the CCW supply rate integral

$$\mathcal{D}(y,z) \approx \int_0^T \dot{y}(t)z(t)dt = y(t)z(t)\Big|_0^T - \int_0^T y(t)\dot{z}(t)\,dt,$$

$$= y(T)z(T) - y(0)z(0) - \int_0^T y(t)\dot{z}(t)\,dt, \tag{18}$$

which after discretizing yields

$$\mathcal{D}(y,z) = y_N z_N - y_0 C z_0 - \sum_{k=0}^{N-1} y_k z_{k+1},$$

$$= y_N C x_N - y_0 C z_0 - \sum_{k=0}^{N-1} y_k \left(C A_d x_k + C B_d u_k \right), \tag{19}$$

where we used $z_k = C x_k$ and $z_{k+1} = C x_{k+1}$. Subsequently, we propose a cost functional composed of a standard running

cost and terminal state cost, augmented with the discretized dissipated energy in (19), such that

$$J(y,x,u) = \sum_{k=0}^{N-1} \left(x_k^\top Q x_k + u_k^\top R u_k \right) + x_N^\top Q_f x_N$$

$$+ \sum_{k=0}^{N-1} y_k^\top W y_k - \sum_{k=0}^{N-1} y_k W C A_d x_k - \sum_{k=0}^{N-1} y_k W C B_d u_k. \tag{20}$$

In order to guarantee positiveness of the cost functional in (20), we rewrite it in matrix form as

$$\Xi := \begin{bmatrix} Q & 0 & -\frac{1}{2}WCA_d \\ 0 & R & -\frac{1}{2}WCB_d \\ (-\frac{1}{2}WCA_d)^\top & (-\frac{1}{2}WCB_d)^\top & W \end{bmatrix} \tag{21}$$

where $Q = Q^\top \succ 0$, $R = R^\top \succ 0$ and $W > 0$ such that $\Xi \succ 0$ and $Q_f = Q_f^\top \succ 0$ for the terminal cost.

B. Optimization Problem Formulation

Consequently, we can cast the modified damage reduction MPC strategy in discrete time as

$$\min_U J := \sum_{k=0}^{N-1} \begin{bmatrix} x_k \\ u_k \\ y_k \end{bmatrix}^\top \Xi \begin{bmatrix} x_k \\ u_k \\ y_k \end{bmatrix} + x_N^\top Q_f x_N \tag{22a}$$

$$s.t. \begin{cases} x_0 = x(t), \\ x_{k+1} = A_d x_k + B_d u_k, \text{for } k = 0,1,\ldots,N-1, \\ x_{\min} \le x_k \le x_{\max}, \text{for } k = 1,\ldots,N, \\ u_{\min} \le u_k \le u_{\max}, \text{for } k = 0,1,\ldots,N, \\ y_0 = y(t), \\ y_{k+1} = \begin{cases} y_k + (\kappa_1 y_k + \mu_1)\,z_{k+1} - z_k, \text{if } z_{k+1} - z_k \ge 0, \\ y_k + (\kappa_2 y_k + \mu_2)\,z_{k+1} - z_k, \text{if } z_{k+1} - z_k < 0, \\ \qquad \text{for } k=0,1,\ldots,N-1, \end{cases} \end{cases} \tag{22b}$$

over $U := \{u_0, \ldots, u_N\}$, for a horizon $N \in \mathbb{N}$, and weights $Q = Q^\top \succ 0$, $R = R^\top \succ 0$, $W > 0$, and $Q_t = Q_t^\top \succ 0$. Note that z_{k+1} in (22b) can be expressed in terms of x_k and u_k.

C. Simulation Results

The proposed damage reduction MPC strategy was implemented in `Matlab`. The wind turbine plant is NREL's FAST non-linear 5MW wind turbine v7 [29] interfaced with `Simulink`. The wind field input has a mean wind speed of 17 m/s. We assumed perfect measurement of the sates, and the initial conditions were set to the steady states. The control strategy was implemented using `Yalmip` [30] with a sampling time of $T_s = 0.15$ s. We chose a horizon $N = 5$ and the weights on the running cost according to Bryson's rule [31, p.537] such that Q and R are diagonal matrices with elements $(1/30^2, 1/0.3^2, 1/0.001^2)$ and $(1/30^2, 1/0.1^2)$, respectively; we let $W = 2.8 \times 10^{-4}$ guaranteeing $\Xi \succ 0$ and $Q_t = 100Q$. The limits on inputs and states are given as $u_{\max} = [90°, 40700 \text{ Nm}]$, $u_{\min} = [0°, 40660 \text{ Nm}]$,

$x_{\max} = [142.9 \text{ rad/s}, 2.27 \text{ rad/s}, 8.5 \times 10^{-3} \text{ rad}]$ and $x_{\min} = [102.9 \text{ rad/s}, 0.27 \text{ rad/s}, 0.5 \times 10^{-3} \text{ rad}]$. For the Duhem semi-linear model in (9) the initial condition was set to $y_0 = 0$ and the coefficients were chosen as $\bar{\kappa}_1 = -1, \bar{\kappa}_2 = 1, \bar{\mu}_1 = b$, and $\bar{\mu}_2 = -b$ with $b = 20$ following [26] for the CCW case. For the drive-train damper in (17) we let $\omega_d = 10.7 \text{ rad/s}, \xi = 0.25 \ \tau = 0.05$ and $G = 400$.
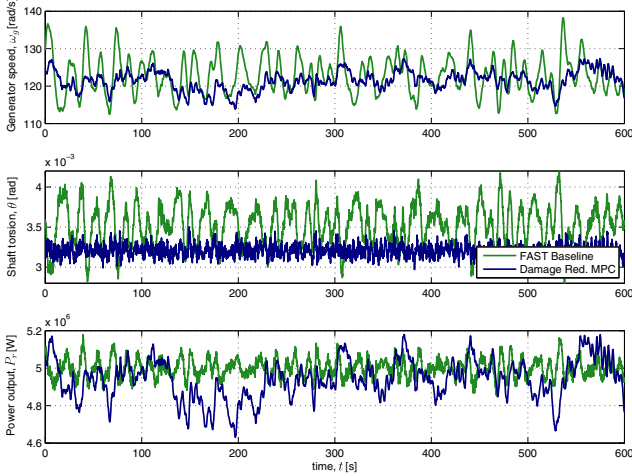

Fig. 2. Generator speed, shaft torsion and output power comparison. FAST baseline controller (green) vs. damage reduction MPC (blue).

Firstly, the proposed damage reduction MPC strategy is compared against the FAST baseline controller; the simulation results are presented in Fig. 2-3, where a comparison of the generator speed, shaft torsion, power output, pitch angle and generator torque are presented. In these figures, one can observe significant improvement in shaft torsion damage, the shaft torsion itself, and the generator torque rate using the proposed active damage reduction strategy. However, the baseline controller is better at pitch rate and power variations. The results are summarized in Fig. 4. The metrics were calculated as follows: *(std)* stands for standard deviation; *(abs)* stands for the total traveled distance and was calculated as $\int \left| \dot{\beta}_p(t) \right| dt$ for the case of pitch rate for example; *(sum)* stands for total accumulation. The damage in the shaft was calculated via rainflow-counting (RFC) using the toolbox presented in [32] with coefficients affine to steel, i.e., $\bar{m} = 4$ and $\log \bar{K} = 15.117$ [33].

Nonetheless, a fairer comparison would be to test the proposed active damage reduction MPC strategy against a nominal MPC strategy without the hysteresis dissipated energy (and consequently without the Duhem hysteresis dynamics in the constraints). Accordingly, the point-wise infinity norm of the difference in the shaft torsion of both cases, the dissipated energy and the shaft torsion damage are shown in Fig. 5. The summary of the comparison between the nominal and the damage reduction MPC strategies is shown in Fig. 6. It is worth mentioning that even though the two strategies are close to each other, the proposed strategy in (22) does achieve some damage reduction in the shaft while increasing the pitch rate.
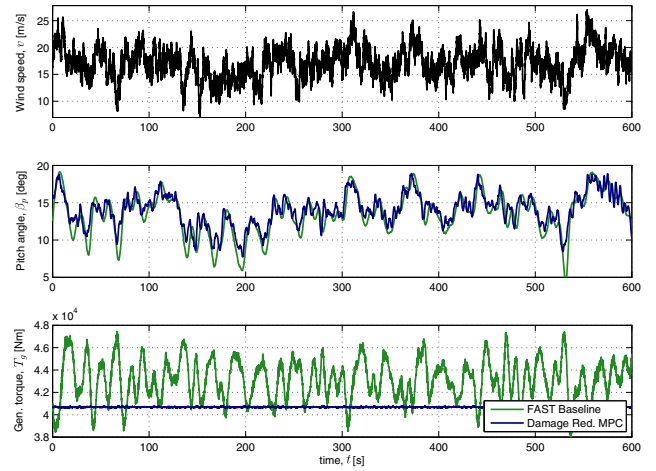

Fig. 3. Wind disturbance (just x−direction shown) and control inputs. FAST baseline controller (green) vs. damage reduction MPC (blue).
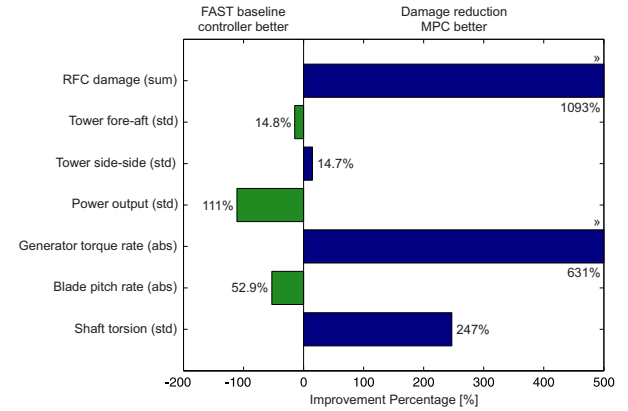

Fig. 4. Metric summary. FAST baseline controller (green) vs. damage reduction MPC (blue).

V. Conclusions

In this paper we proposed an active damage reduction control strategy for wind turbines based on the dissipated energy provided by a Duhem hysteresis operator. Due to the infinite dimensional memory characteristic of the Preisach model, we use the dissipated energy of the Duhem hysteresis model, since it can be explicitly written as a differential equation and facilitates its inclusion in optimal control problems. We provide simulation results using NREL's FAST 5MW non-linear wind turbine, where we illustrate the applicability of the proposed control strategy which incorporates the dissipated energy using the shaft torsion as input as a damage proxy. The results show the well-known trade-off allowing reduction in the states variations but increasing pitch activity and power fluctuations. Furthermore, even though the proposed strategy shows a big difference against the FAST baseline controller, it is only slightly better that the nominal MPC but also increasing pitch activity that can lead to wear, adding fluctuations in the power and resulting in a non-convex optimization problem.
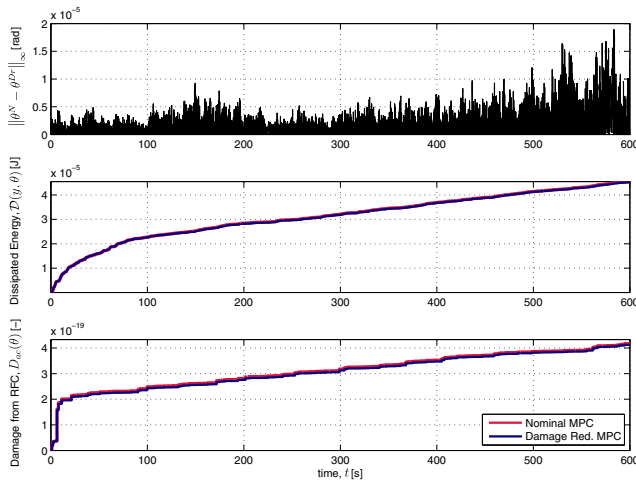
Fig. 5. Shaft torsion difference, dissipated energy and RFC damage. Nominal MPC (red) vs. damage reduction MPC (blue).
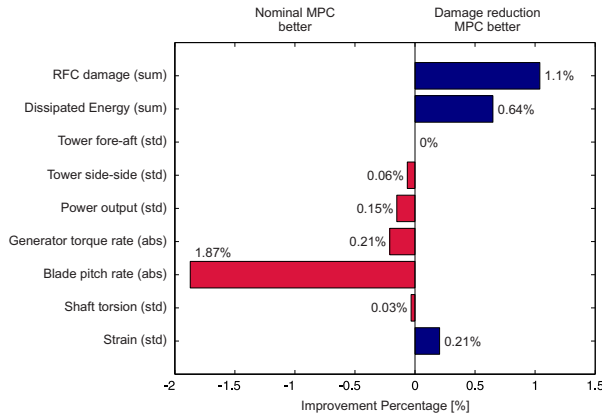

Fig. 6. Metric summary. Nominal MPC (red) vs. damage red. MPC (blue).

VI. ACKNOWLEDGMENTS

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