DIELECTRIC BARRIER DISCHARGE (DBD) BASED PLASMA ACTIVATION IN HORIZONTAL AXIS WIND TURBINE USING MODEL PREDICTIVE CONTROL LOGIC FOR IMPROVED PERFORMANCE

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Abstract

The active flow control of rotor blades decides the efficiency of the wind turbine. This active flow control of wind turbine also has a major role in the fatigue loading of turbine components. The Plasma actuator is one such active flow control technique which precisely achieves the power efficiency of the wind turbine in a highly stochastic wind field. This plasma actuator involves virtual mechanical moving parts and application of high voltage at various span of the blade. But the serious detriment of this plasma actuator is that the ON-OFF based plasma actuation intrudes fatigue loading of the turbine components, especially on the blades. This is due to the unspecific change in the aerodynamic lift while activating plasma actuator. This fatigue load has a serious effect on the life-time of the structural components. In order to overcome this difficulty in plasma actuators, a novel methodology involving the azimuthal angle based predictive plasma level switching is proposed in this work. The Multiple-model predictive algorithm is used for controlling the plasma level at various azimuthal angles of the blade. The NREL FAST 5MW baseline wind turbine is used for analysis. The proposed methodology is validated using Fatigue life analysis by MLife software of NREL.

Keywords: Active *flow control; aerodynamic lift; azimuthal angle; fatigue loading; Multiple-MPC algorithm; plasma actuator*.

Introduction

The Wind energy has become an unavoidable source of renewable energy sources. Sustainable development of renewable energy in renewable energy source is nothing without the sustainable improvements in the wind energy production. The report from the Global wind energy Council reflects the same by its projected statistics that the wind energy installation will be around 800GW in 2020 [1]. This increased dependence global power market on wind energy sources, imposes the idea of increasing the size of wind turbine exponentially [2]. In the present scenario typical wind turbine specification of tower height is around 100 m and the top edge blade height is 140 m which is far away from the contemporary models. These increased size wind turbine naturally often exposed to an extreme aerodynamic environments and susceptible to peak structural forces. These fatigue aerodynamic forces intrudes a detrimental vibration on the turbine components. The prolonged vibration of the components would lead to complete failure of the system. The decrease in the life-time of the wind turbine makes it economically unviable [3-5].

This makes the fatigue load mitigation, a most significant area of research in recent years. The major components susceptible to the aerodynamic stress are the blades and the tower. The flap-wise and the edge-wise bending moments are the major modes of the vibration in blades. Since the blades cover the major part in the total cost of the wind turbine, improvement in the life-time of the blades would solve the economic trait of the wind energy. Most of the researches confine themselves the dynamic response of the wind turbine with respect to the cut-in and cut-out of wind. The extreme environment dynamic analysis of wind turbine remains unexplored. The extreme wind speed ranges from 25-40 m/sec. The wind turbine rotor dynamics changes with respect to the azimuthal angle of the blades. The azimuthal angle represents the position of each blade in the 360^0 span of rotor. Each blade is equally displaced at an angle of 120^0. The dynamics of the blades at each azimuthal angle change in such a way that the blade at the top is susceptible to extreme fatigue stress than the blade at the bottom. The effective control of fatigue stress of the wind turbine could be achieved by i) active, ii) passive and iii) semi-active methods of active flow control. The flow control technique involves the alteration aerodynamic profile in order to mitigate the fatigue part of the aerodynamic lift force [6,7]. The active flow control technique includes the individual pitch controller, deformable trailing edge flaps, active aerodynamic vortex generators, aero-blowers, micro jets, plasma actuators, etc. Amidst the other AFC methods which involve a mechanical or hydraulic actuation and a deforming of a span or the entire blades structure, the plasma actuator holds an inherent benefit of free from mechanical actuation.

The Plasma actuator circuit requires a minimum alteration in the typical bade structure. The Plasma effect in wind turbine blades could be intruded by the application of high voltage on the exposed electrode of the plasma circuit. As the plasma effect is activated the aerodynamic profile of the blade changes and the coefficient of lift is altered. It could be both used for positive and negative side of power output. The increase in the lift coefficient substantially increases the power output. But to the detrimental part of plasma actuator the fatigue stress on the blades also increase drastically in extreme gust. This has serious effect on the structural life-time of the turbine components.

In order to resolve this issue arose in ON-OFF based activation of plasma actuator, a novel fuzzy switched multiple-model predictive controller based variable plasma actuation strategy is proposed. The model predictive algorithm is apt for predicting the response of the system at various azimuthal angle of blade. The predictive response of the system could be used implement the control action required at particular operating point in advance. The control action would be the intensity of plasma activation which is altered using the level of voltage applied on the electrode [8,9]. Hence the manipulating variable is the plasma level which is manipulated using the intensity of the voltage applied. The proposed control strategy is validated using the fatigue life analysis of the simulation results.

This paper is organized as the second part elaborating the variable plasma effect, the third part explaining the linearization of non-linear wind turbine system, the fourth part explaining the features and structure of fuzzy switched Multiple-MPC controller, fifth part fatigue life analysis, the sixth section detailing about the simulation setup , seventh section discussing the simulation results & fatigue life analysis data and conclusion based on the results obtained in the last section of the work.

2. VARIABLE PLASMA EFFECT

The plasma effect on wind turbine blades could be obtained by incorporating the plasma circuit in a particular span of blade where it is optimally required. The plasma circuit consists of two electrodes and a dielectric layer. One of the electrodes is exposed to the external surface and the other electrode is encapsulated inside the dielectric layer of the blade surface. The plasma effect works on the principal of movement of extreme momentum fluid from the free stream into the edge of the blade. The Extra-high voltage (EHV) applied on the external electrode initiates the discharge of charged particles moving towards the negative encapsulated anode, is called the "Plasma". This movement of the charged particle induces a momentum in the air surrounding the blades surface. This agitated momentum induced increases the aerodynamic lift coefficient and substantially alters the aerodynamic profile of the surface around the blade [10,11]. The intensity of the plasma could be altered by manipulating the following:

i) Distance between the two electrode
ii) Magnitude of voltage applied
iii) Frequency of the AC supply applied.

In this work the voltage magnitude is to be manipulated airfoil data is to be used in FAST aerodyne to alter the intensity of the 'Plasma'. The variation in the aerodynamic profile of the area surrounding the span of blade influenced by the 'Plasma effect' and the lift coefficients are manipulated proportionally with respect to the voltage level of plasma activation. The controlled variation in the intensity of the 'Plasma effect' would provide the effective control and maneuvering the aerodynamic lift coefficient, thereby the fatigue loads in extreme wind conditions could be damped. The experimental data of lift coefficients for varied intensity of plasma by maneuvering the magnitude of voltage V1, V2, V3, V4 and V5 are illustrated in Fig.1.C_L is the coefficient of lift which is altered by the plasma activation. The 'Plasma Level' 1 to 'Plasma Level 5' are the intensity of the plasma activation in applying the voltage of magnitudes from 5-11 kV (V1 – V5) respectively. The experimental data for various levels Plasma which is directly proportional to the magnitude of applied voltage at blade surface is obtained from NREL benchmark turbine from [15]. The major disadvantage of this method of active flow control in wind turbine is the application of Extra High Voltage (EHV) at the tip of the blade when the blade is at the top side of the rotor which is currently ignored. The detailed modelling of plasma actuator in NREL FAST software is explained simulation setup session. The geometrical specification of plasma circuit is tabulated in Table. I.

Table.I. Specification of DBD Plasma actuator

Parameter	Geometrical value
Length of encapsulated electrode (L_{en})	0.7m
Length of exposed electrode (L_{exp})	0.6m
Thickness of dielectric (T_d)	0.03m
Thickness of electrode (T_e)	0.03m
Relative permittivity (ε_{rd})	4.2

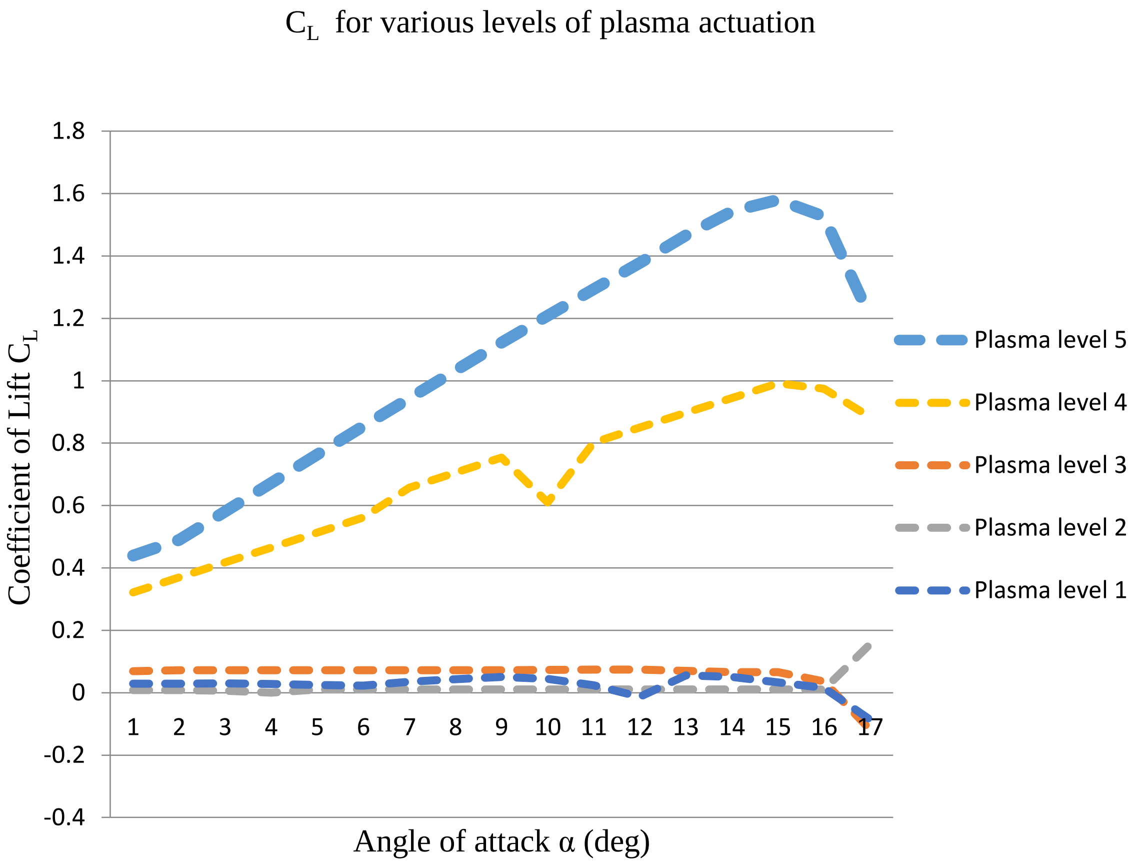

Fig.1. Coefficient of Lift (C_L) values for various levels of plasma actuation.

3. LINEARIZATION OF FAST NON-LINEAR MODEL

The NREL FAST 5MW baseline model is to be used as the benchmark model for this work. The non-linear FAST wind turbine model could be linearized for various azimuthal angles of the rotor blades and linearized state space model could be obtained by MBC software of NREL [11,16]. The DOFs with respect to the blade bending moment and generator torque are enabled for linearization process. The linearized model is obtained for an extreme wind speed of 35 m/sec. The linearized model is obtained in the form as below [17] in Eqs(1),(2).

$$\dot{X}_{k+1} = A_k X_k + B_k U_k \quad (1)$$

$$Y_k = C_k X_k \quad (2)$$

X_k- System Matrix

Y_k- System output

U_k- Control Input

A_k, B_k, C_k- Discrete system Matrices.

The linearized model of the non-linear wind turbine is obtained at operating point of azimuthal angles 0^0, 45^0, 90^0, 135^0, 180^0,225^0,270^0,315^0, and 360^0. The obtained linearized models are validated for unique system response using gap metric algorithm. This gap metric algorithm is used to avoid the overlapping of the system dynamic response. If two consecutive models possess similar dynamic characteristics then the gap metric value would be very less based on which alternate model at another operating point could be placed in the slot.

4. FUZZY SWITCHED MULTIPLE-MPC CONTROLLER

The Model predictive controllers are evolving faster in recent trend due to its multi-aspect advantages. The predictive nature of the controller with the linear model of the system enables the easy preview of the system response to a substantial level of accuracy. This preview response paves way for anticipatory control action in the system so that the efficient damping of disturbance is guaranteed. The model predictive algorithm effectively manages the system non-linearity's and also has an inherent ability to handle the constraints imposed on input and output of the system. The predictive algorithms used in this work are derived as in Eqs (3-4);

$$X_{k+1} = A_k X_k + B_k U_k$$

$$X_{k+2} = A_k^2 X_k + A_k B_k U_k + B_k U_{k+1}$$

$$X_{k+3} = A_k^2 \left[A_k X_k + B_k U_k \right] + A_k B_k U_{k+1} + B_k U_{k+2}$$

$$\vdots$$

$$X_{k+N_P} = A_k^{N_P} X_k + A_k B_k U_{(k+N_P-1)} + A_k B_k U_{(k+N_P-2)} + \cdots + A_k^{N_P-1} B_k U_k \quad (3)$$

Similarly the output equation is derived as in Eqs(4-6);

$$Y_{k+1} = C_k(A_k X_k + B_k U_k)$$
$$Y_{k+2} = C_k(A_k^2 X_k + A_k B_k U_k + B_k U_{k+1})$$
$$Y_{k+3} = C_k(A_k^2[A_k X_k + B_k U_k] + A_k B_k U_{k+1} + B_k U_{k+2})$$
$$\vdots$$
$$Y_{k+N_p} = C_k A_k^{N_p} X_k + C_k A_k B_k U_{(k+N_p-1)} + C_k A_k B_k U_{(k+N_p-2)} + \cdots + C_k A_k^{N_p-1} B_k U_k \tag{4}$$

The value of prediction horizon N_p should be greater than the control horizon N_c . The above equations could be summarized as:

$$\underbrace{\begin{bmatrix} x_{k+1} \\ x_{k+2} \\ x_{k+3} \\ \vdots \\ x_{k+N_p} \end{bmatrix}}_{X_k} = \underbrace{\begin{bmatrix} A_k \\ A^2{}_k \\ A^3{}_k \\ \vdots \\ A^{N_p}{}_k \end{bmatrix}}_{P_x} X_K + \underbrace{\begin{bmatrix} B_k & 0 & 0 & \cdots \\ A_k B_k & B_k & 0 & \cdots \\ A^2{}_k B_k & A_k B_k & B_k & \cdots \\ \vdots & \vdots & \vdots & \vdots \\ A^{N_p-1}{}_k B_k & A^{N_p-2}{}_k B_k & A^{N_p-3}{}_k B_k & \cdots \end{bmatrix}}_{H_x} \underbrace{\begin{bmatrix} U_k \\ U_{k+1} \\ U_{k+2} \\ \vdots \\ U_{k+N_p-1} \end{bmatrix}} \tag{5}$$

$$\underbrace{\begin{bmatrix} Y_{k+1} \\ Y_{k+2} \\ Y_{k+3} \\ \vdots \\ Y_{k+N_p} \end{bmatrix}}_{y_k} = \underbrace{\begin{bmatrix} C_k A_k \\ C_k A^2{}_k \\ C_k A^3{}_k \\ \vdots \\ C_k A^{N_p}{}_k \end{bmatrix}}_{P} X_K + \underbrace{\begin{bmatrix} C_k B_k & 0 & 0 & \cdots \\ C_k A_k B_k & C_k B_k & 0 & \cdots \\ C_k A^2{}_k B_k & A_k B_k & C_k B_k & \cdots \\ \vdots & \vdots & \vdots & \vdots \\ C_k A^{N_p-1}{}_k B_k & C_k A^{N_p-2}{}_k B_k & C_k A^{N_p-3}{}_k B_k & \cdots \end{bmatrix}}_{H} \underbrace{\begin{bmatrix} U_k \\ U_{k+1} \\ U_{k+2} \\ \vdots \\ U_{k+N_p-1} \end{bmatrix}}_{\underset{\rightarrow}{U}_{k-1}} \tag{6}$$

Thus the equation of prediction for the specified horizon is summarized as in Eqs (7)(8):

$$X_{\rightarrow k} = P_X X_k + H_X U_{\rightarrow k-1} \tag{7}$$
$$Y_{\rightarrow k} = P X_k + H U_{\rightarrow k-1} \tag{8}$$

Though the system is uncertain, its states are known hence no estimations are needed.

In this work the voltage manipulated plasma level switching is the major manipulating variable and the switching rate is the most critical parameter to be minimized. Therefore the online control law is framed by minimization cost function J with respect to control horizon N_p that is Δu . Optimizing Δu the first element is implemented as the optimization process is repeated at each sampling instant as in Eqn(9).

$$\min_{\underset{\rightarrow}{\Delta u}} J = \sum_{i=0}^{N_p} \left\| \underset{\rightarrow}{e} \right\|_2^2 + \lambda \sum_{i=0}^{N_C} \left\| \underset{\rightarrow}{\Delta u} \right\|_2^2 \tag{9}$$

The most attractive property of Model Predictive Controller (MPC) is its explicit constraint handling. In case of sensitive system like wind turbine this inherent ability of the MPC is used to limit the control inputs. The plasma level switching and switching rate are the critical parameter to be kept within the permissible range to ensure the stability of the wind turbine [18-20]. The MPC1…MPC8 in Fig.2 are the MPC objective functions at various wind conditions between 8m/sec to 35m/sec. To facilitate this facility the constrains are framed as in Eqs(10);

Input constrains:

$$\underline{u}_{IP} \le u_{IP} \le \overline{u}_{IP}$$
$$\underline{\Delta u}_{IP} \le \Delta u_{IP} \le \overline{\Delta u}_{IP} \tag{10}$$

Where

$\underline{u}_{IP}$ -Minimum value of Individual pitch angle which is '0'

$\overline{u}_{IP}$ - Maximum value of Individual pitch angle which is kept as 1.5rad.

$\underline{\Delta u}_{IP}$ - Minimum value of Individual pitch angle rate which is kept as '0'

$\overline{\Delta u}_{IP}$ -Maximum value of Individual pitch angle rate which is kept as 0.139 rad/s

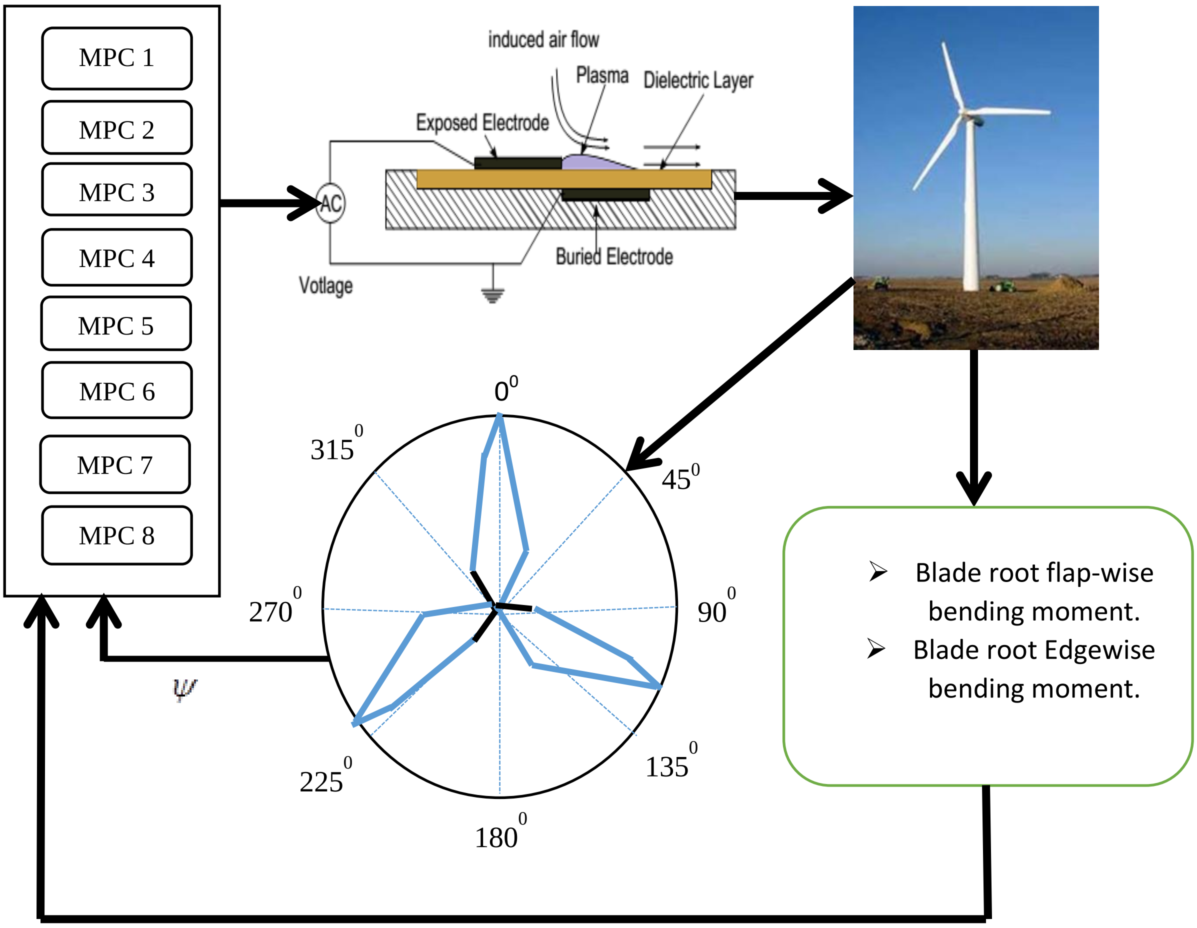

Fig.2. Graphical abstract.

5. FATIGUE LIFE ANALYSIS

The statistical analysis of the measured output and the prediction of life time damage of the components is used to validate the effectiveness of the proposed controller. The prolonged fatigue damages faced by the turbine components could be aggregated to estimate the life-time damages of the wind turbine. This post processing operation is done by the MLife software of NREL [14,15]. The integrated fatigue load termed as Damage Equivalent Load (DEL) is estimated for short term and long term operation of wind turbine. The parameters below are estimated by MLife software which could be used for life-time prediction of wind turbine components.

i) Short term Damage Equivalent Loads (DEL)
ii) Damage rates

The life time calculations include:

i) time until failure
ii) lifetime DEL

The damage equivalent load (DEL) is a constant amplitude fatigue that occurs at constant load mean and frequency such that they produce the equivalent damage as the load spectrum varies as in Eqs(11).

$$D_j^{ST} = \sum_i \frac{n_{ji}}{N_{ji}} = \frac{n_j^{STeq}}{N_{ji}}$$

$$n_j^{STeq} = f^{eq} T_j$$

$$N_j^{eq} = \left(\frac{L^{ult} - \left|L^{MF}\right|}{\left(\frac{1}{2} DEL_j^{STF}\right)} \right)^m \qquad (11)$$

Where f^{eq} is the DEL frequency , T_j is the elapsed time of rime series j, n_j^{STeq} is the total equivalent fatigue count for time series j, N_j^{eq} is the equivalent number of cycle until failure for time series j. This gives Eqs(12),(13):

$$DEL_j^{STF} = \left(\frac{\sum_i \left(n_{ji} \left(L_{ji}^{RF} \right)^m \right)}{n_j^{STeq}} \right)^{\frac{1}{m}} \quad (12)$$

in case of zero mean the L^{MF} is kept as zero

$$DEL_j^{STF} = \left(\frac{\sum_i \left(n_{ji} \left(L_{ji}^{RO} \right)^m \right)}{n_j^{STeq}} \right)^{\frac{1}{m}} \quad (13)$$

Where L_{ji}^{RO} the adjusted load is ranges about a zero fixed mean.

MLife calculates short term time series based DEL, without using the Goodman correction such that $L_{ji}^{RF} = L_{ji}^{R}$ and where L^{MF} equal to zero.

$$DEL_j^{STF} = \left(\frac{\sum_i \left(n_{ji} \left(L_{ji}^{R} \right)^m \right)}{n_j^{STeq}} \right)^{\frac{1}{m}} \quad (14)$$

The life time damage equivalent loads are computed by aggregating the fatigue cycles from all time-series. The life time cycles are calculated using lifetime count extrapolation factor f_j^{Life} and the short term equivalent count n_j^{STeq} as in Eqs(15) such that

$$n_j^{STeq} = \sum_j f_j^{Life} n_j^{STeq} \quad (15)$$

Here the lifetime damage to variable fatigue cycles to the damage resulting from a repeating equivalent load

$$D^{Life} = \sum_j \sum_i \frac{n_{ji}^{Life}}{N_{ji}} = \frac{n^{Life,eq}}{N^{eq}} \quad (16)$$

The lifetime fatigue equivalent load about fixed mean is computed by Eqs(17),

$$DEL^{LifeF} = \left(\frac{\sum_j \sum_i \left(n_{ji}^{Life} \left(L_{ji}^{R} \right)^m \right)}{n^{Life,eq}} \right)^{\frac{1}{m}} \quad (17)$$

The lifetime fatigue equivalent load using zero mean is computed by Eqs(18),

$$DEL^{LifeFO} = \left(\frac{\sum_j \sum_i \left(n_{ji}^{Life} \left(L_{ji}^{RO} \right)^m \right)}{n^{Life,eq}} \right)^{\frac{1}{m}} \quad (18)$$

The lifetime fatigue equivalent load about Zero mean without Goodman Correction is computed by Eqs(19),

$$DEL^{LifeF} = \left(\frac{\sum_j \sum_i \left(n_{ji}^{Life} \left(L_{ji}^{R} \right)^m \right)}{n^{Life,eq}} \right)^{\frac{1}{m}} \quad (19)$$

6. SIMULATION SETUP

This work uses NREL FAST 5MW Baseline online wind turbine as the benchmark system. The rotor conFiguration of the FAST 5MW turbine is modulated in order to enable the Plasma activation. The changes to be implemented in the normal aerodyne of FAST are the airfoil data which is being obtained by wind tunnels with inbuilt plasma actuator. In a normal NREL 5MW wind turbine blade conFiguration there are 7 airfoils from root to tip of blade. The airfoil data of the fraction of blade where plasma effect is to be incorporated is replaced with the polar altered data of plasma induced airfoil. In this work the plasma is to be placed at the trailing edge of the blade [10].

As shown in Fig. 1. 'X' is the fraction of blade where the 'Plasma' effect is to be implemented then the seventh airfoil of the blade is replaced by five different airfoils. These five airfoils contain the coefficient of the blade with different intensity of plasma actuated i.e. based on different voltage triggered for plasma actuation. The arrangement of the airfoil in the full length blade is altered such that the trailing edge airfoil NACA64618 at the span of 61.5m is replaced with the airfoil data V_1, V_2, V_3, V_4 andV_5, designed using QBlade software with the C_L and C_d data from [11]. The polar data is obtained by the coefficient and they are extrapolated to 360° AOA using QBlade software [12]. The schematic representation of plasma activation in a fraction of blade with N elements, each with its own chord *c*, radial size *dr* and radial distance *r* is shown in Fig. 1-2.

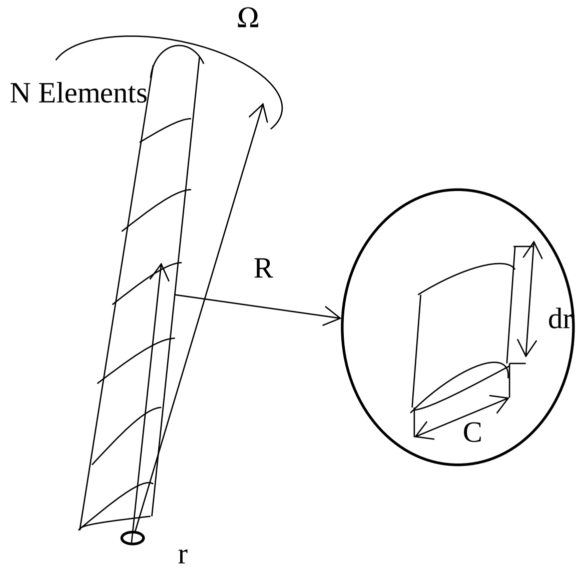

Fig.3. Airfoil of a blade

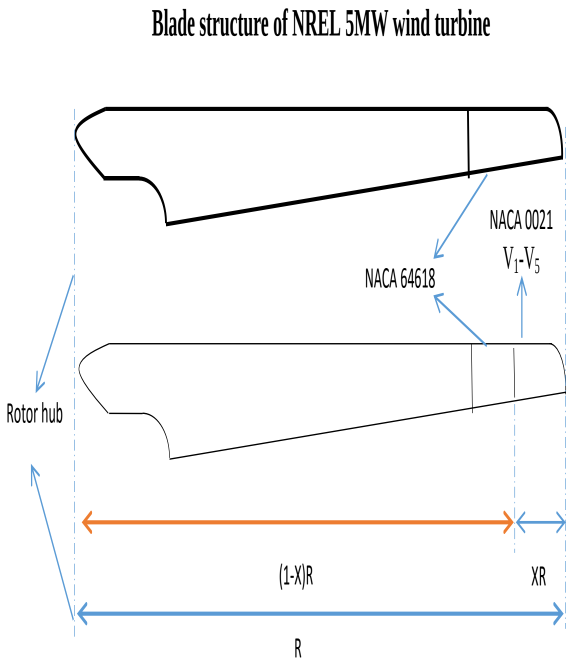

Fig.4.The blade fraction xR where plasma effect is investigated is replaced with plasma actuated airfoils V_1-V_5.

The NREL TurbSim software is used to simulating the non-linear wind field required for analysis of the proposed control strategy. The kaimal turbulence model is used in the wind field simulation [13,14]. The average wind speed chosen is 35.5 m/sec which is an extreme condition wind flow. The Table.II tabulates the DOFs enabled in NREL FAST 5MW wind turbine model.

Table.II. Degrees of freedom enabled

Structural Element	Number Of DOFs	Description
Blade	2	Flap-wise bending mode per blade
	1	Edgewise bending mode per blade
Nacelle	0	Yaw maneuvering
Drive Train	0	Drivetrain rotational-flexibility
Generator	1	Variable speed generator
Tower	2	Tower fore-aft bending mode
	2	tower side-to-side bending mode DOF

7. RESULTS AND DISCUSSION

This section of the work illustrates and discusses the simulation results of the wind turbine in various operating conditions. The simulation results consists of output waveform of the blade root bending moment both flap-wise and edge-wise at various operating conditions like Plasma OFF, Plasma ON (full plasma) and at azimuthal angle based fuzzy switched MPC controlled variable plasma activated. The above mentioned analysis results are shown in Fig.5-9.

The Fig.5-9 shown below are the simulation results of the NREL FAST wind turbine model with Plasma integration, intensity of which is manipulated using Multiple point model predictive control logic. For the consideration of this work the fatigue parameter individual blade root bending moments (both flap-wise and edge-wise) are chosen. The Fig.5-6, illustrates the flap-wise and edge-wise bending moments under various plasma operating conditions [18-20]. The Fig.7 shows the azimuthal angle of blades for switching the plasma intensity. The Fig.8-9 showing the power output of the wind turbine and the control action of the MPMPC controller in switching the intensity of the Plasma actuator.

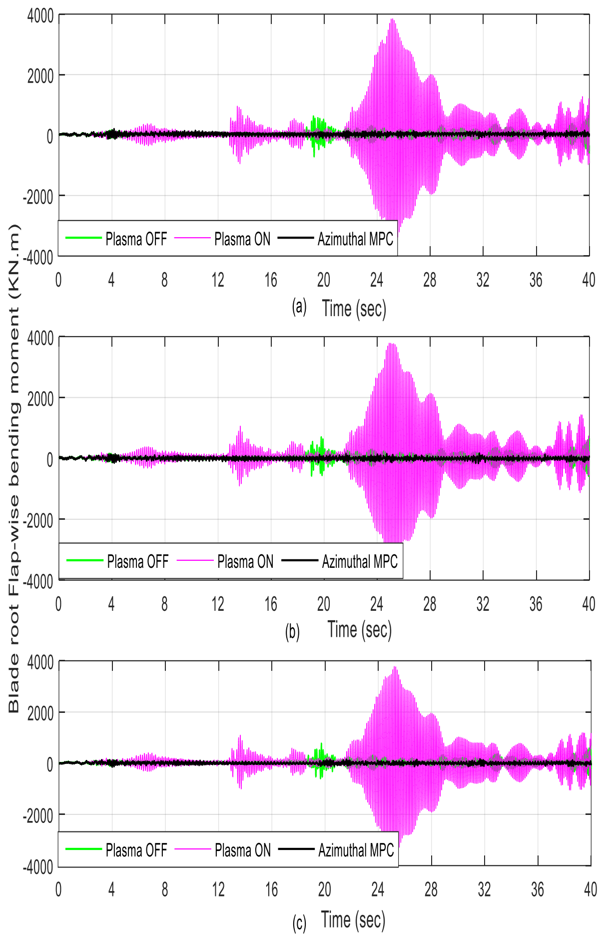

Fig.5. Flap-wise bending moment of turbine, a) blade 1, (b) blade 2 and (c) blade 3

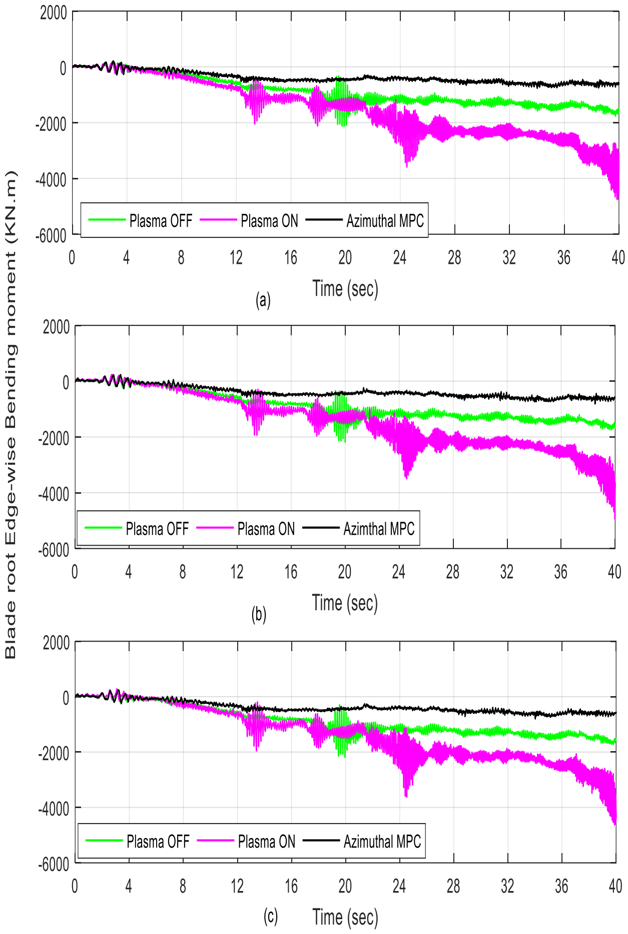

Fig.6. Edge-wise bending moment of turbine a) blade 1, (b) blade 2 and (c) blade 3

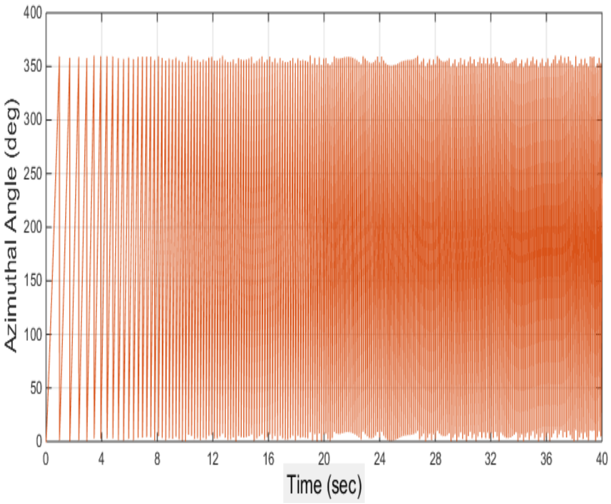

Fig.7. Azimuthal Angle of turbine

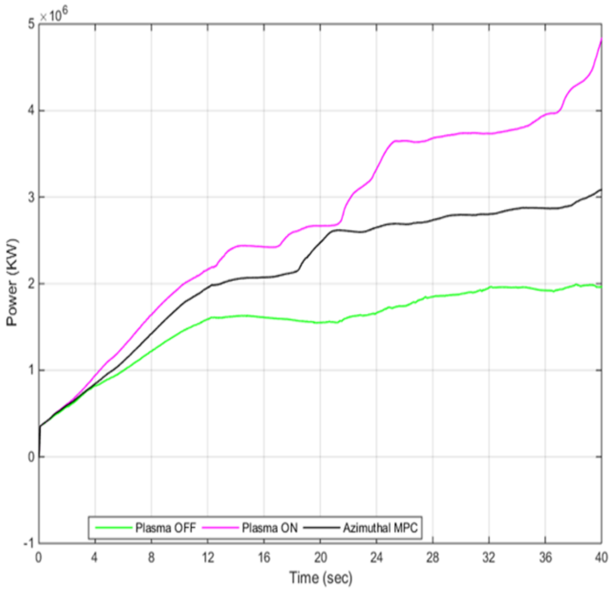

Fig.8. Power output of wind turbine using different operating condition.

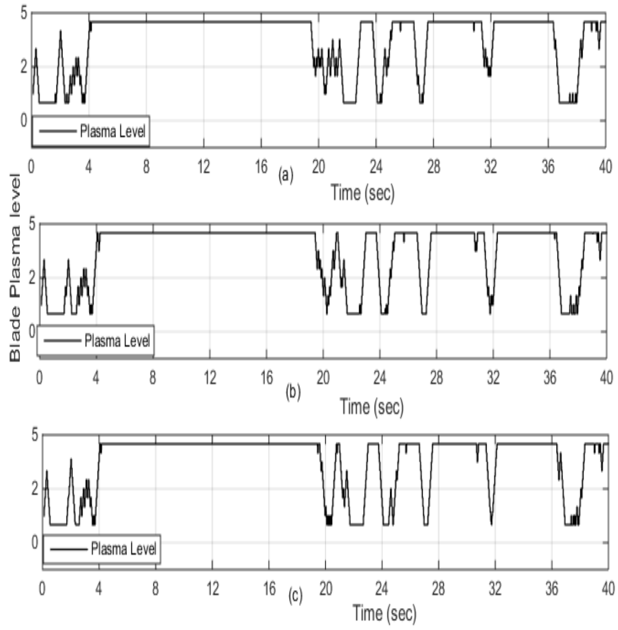

Fig.9. Control action from the proposed control strategy a) blade 1, (b) blade 2 and (c) blade 3

The above results make it easy to infer that the plasma actuation using proposed azimuthal angle based fuzzy switched multiple-MPC controller produces a tremendous level of fatigue load mitigation while compared to ON-OFF based plasma operation. The power compromise with respect to the plasma –OFF mode of operation of wind turbine is within acceptable limit. Since the life-time of the components holds more priority than the momentary power compromises, the proposed novel method of plasma actuation makes the wind power more economically viable. The life-time DEL analysis of the wind turbine blades are used to predict the lifetime of the rotor blades.

7.1. FATIGUE LIFE ANALYSIS

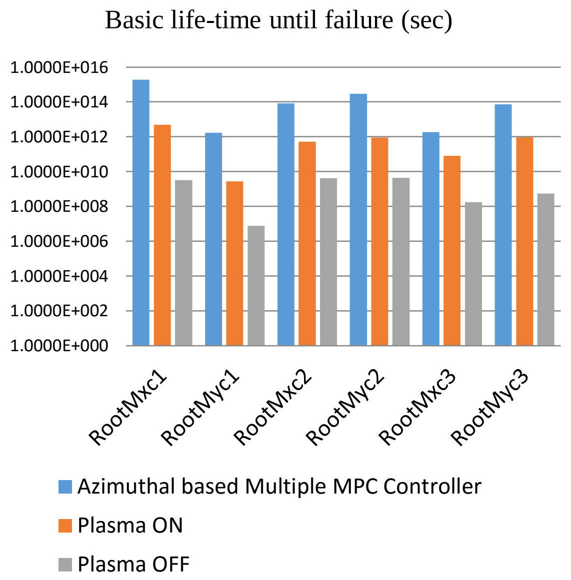

Fig.10. Basic lifetime until failure in (sec) for the individual blade root bending moment in different operating conditions

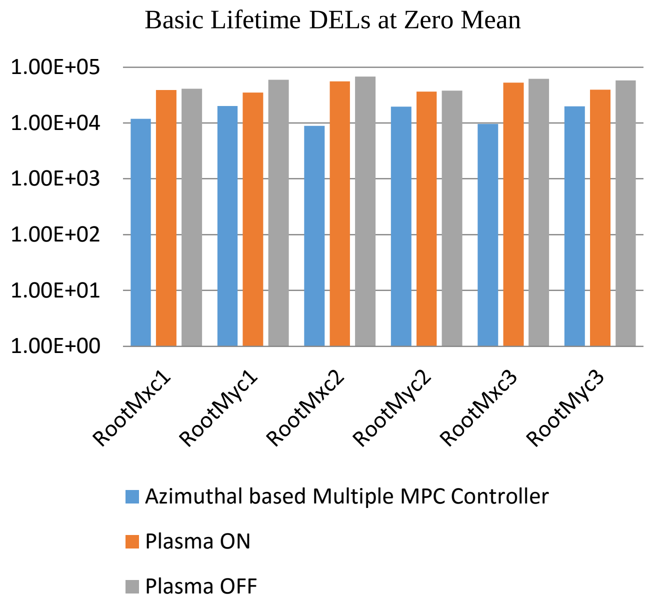

Fig.12. Basic Lifetime DELs in for the individual blade root bending moment in different operating conditions.

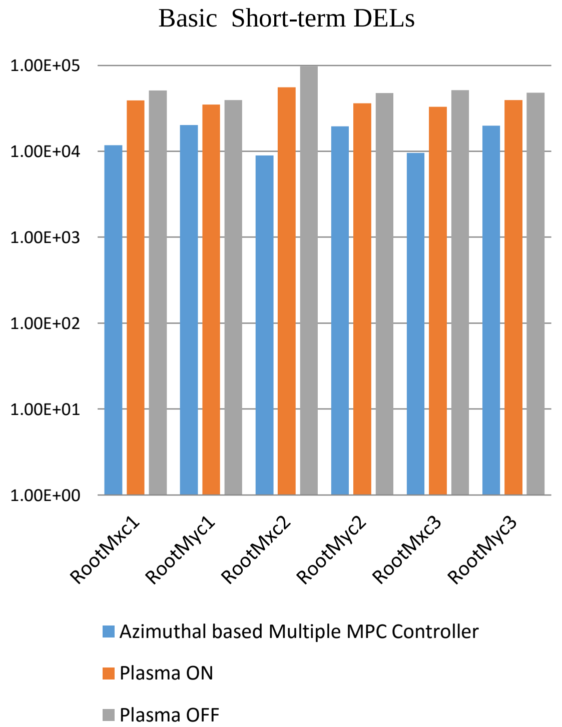

Fig.11 .Basic short term DELs for the individual blade root bending moment in different operating conditions.

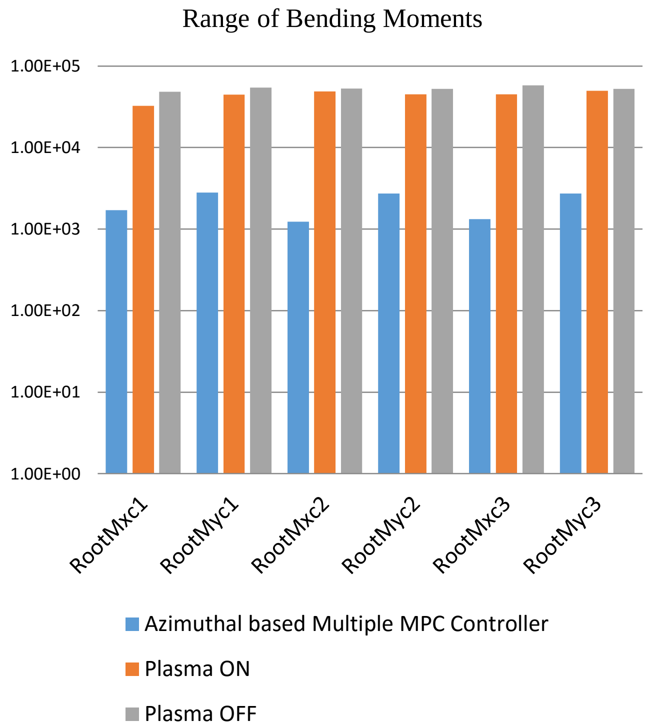

Fig.13. Range of individual blade root bending moment in different operating conditions.

The summary of the statistical results from the histograms shown in Fig.10-13 are tabulated in tables III and IV. The summarized tabulated results exhibit the efficiency of the proposed control logic.

Table.III. Comparison of fatigue load Efficiency of the proposed controller over the other controllers for blade root bending moment.

Fatigue Load Calculations	Parameters	Percentage of the proposed control strategy over ON-OFF plasma actuation	
		Plasma OFF (%)	Plasma ON (%)
Lifetime Damage equivalent Load(DEL)	Blade averaged root Flap- wise bending moment	20.22	85.44
	Blade averaged root edge- wise bending moment	19.33	86.82
short term DELs	Blade averaged root Flap- wise bending moment	23.22	88.9
	Blade averaged root edge- wise bending moment	15.5	87.34

Table.IV. Comparison of Lifetime Efficiency of the proposed controller over the other controllers for blade root bending moment

Lifetime Analysis	Parameter	Plasma OFF (sec)	Plasma ON (sec)	Azimuthal based MPC Controller (sec)
Lifetime until failure	Blade averaged root Flap-wise bending moment	2.47e+09	1.24e+12	2.20e+13
	Blade averaged root edge- wise bending moment	1.798e+09	4.68e+11	1.62e+13

It is easy to infer from the table above that the MPMPC based plasma level switching in the active flow control of wind turbine exhibits extremely good response. The above table showing the comparative statistical results makes it clear that the proposed control logic improves the lifetime of the wind turbine components exponentially and also improves the power capturing capacity of the wind turbine.

8. CONCLUSION

The plasma actuator is an evolving, wear and tear free active flow control method with many advantageous features. The minor detrimental aspects of the plasma actuator are the inducement of the fatigue loads on the turbine components which using ON-OFF based activation. The proposed plasma actuation strategy effectively damps the fatigue loads on the wind turbine blades and it improves the life-time of the turbine components exponentially. The proposed method improves the life-time of the turbine blade exponentially and reduces the fatigue bending moment on blade root by ~85% when compared to ON-OFF based plasma activation. The proposed methodology resolves the economic issues surrounding the plasma actuation method and makes it a more efficient method. The extension of this work would be the inclusion of effects of induced downstream wake in calculating the fatigue loads and implementing artificial intelligence to predict the evolution of wind field.

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