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Maximum power point tracking control for wind turbines with battery storage system

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ABSTRACT

In wind energy conversation systems (WECS), power quality and energy conversion efficiency are crucial aims of control algorithms. These two points are self-contradictory and difficult to trade off where enhancing the efficiency of conversion may also enhance instability of output signal as well. In current work, we submit a wind turbines control scheme to ensure regular power and achieve variable load requests in battery based variable speed PMGS system. In the submitted scheme, model predictive control (MPC) is joint with fuzzy logic to achieve the advantages of these two diverse approaches. The suggested controller could enhance the power reliability performance of the wind turbine. According to obtained results, the proposed topology overcomes the traditional proportional/integral (PI) model by achieving profits in the context of step-overshoot response and the measure of total harmonic-distortion of nearly 1.1 percent and 1.13 percent, respectively.

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1. INTRODUCTION

Wind green resource has been one of the key renewable_energy resources to develop and apply due to global warming and growing load requirements [1]. In this respect, for a number of decades, control techniques of wind energy plants have been investigated through a lot of studies. Nevertheless, the control strategies topic is yet an open issue for researchers. According to the essential purpose of the controller, the wind turbine controller can be one of two types. On one hand, the maximum power tracking algorithm, i.e., MPPT, in which the object is to fulfil the effective conversion of wind energy. On the other hand, for turbines run above normal wind-speed, the main control object is system power quality in addition to the efficiency of energy-conversion [2]. Besides the aforementioned issues, one of the crucial challenging tasks is the management of the existing networks to keep a normal generator functionality in case of a disturbance occurrence, i.e., fault ride through (FRT) of the system. In these respects, power-conversion efficiency and power-fluctuation reduction have been considered, separately, in-depth (see for example [3] and references therein). However, improving the quality of power without employing energy storage tools could result in system capability lack where many power-qualities improving approaches depend on using off energy-storage devices. J. Hussain *et al.* [2] introduce a new adaptive MPPT regime to address the issues mentioned previously i.e., power quality and enhancing energy efficiency. E. Iyasere *et al.* [4] introduces a robust controller as a modern paradigm WT enhancement scheme. Boukhezzar *et al.* in [5] suggest a nonlinear control for wind turbine schemes. Zhang *et al.* in [6] propose a novel maximum power point tracking (MPPT) technique via the strengthening of a learning technique (network based) to address the fluctuations of the system situation. Model predictive technique (MPC) schemes can cope with the issues of linear and nonlinear constraints in multi-objective optimization problems. Consequently, in [7-10] apply this approach, i.e., MPC in the machine side controller (MSC). P. Kou *et al.* [11], MPC has been utilised for battery-based wind turbine controller. Cannon *et al.* [12] used the MPC approach for improving the efficiency of energy conversion and the mechanical load. In [13, 14] address the issue of multi objective control in WT employing the technique of MPC. In [15], authors consider issues of energy conversion and drive train loads via the technique of MPC. D. Q. Mayne *et al.* [16] address the stability issue in MPC strategy employing a terminal quality-constraint. M. Soliman *et al.* [17], authors provide a model predictive scheme in which the system is adapted w.r.t condition of the wind where linear process is needed in the modelling of MPC scheme. A tuning scheme is suggested by reference [18] utilising the design of sensitivity tables. In [19], Bououden *et al.* address control performance and system efficiency by Appling a fuzzy logic based MPC technique. A. Kusiak *et al.* [20], weights for various wind speed conditions are modified by data classification. H. F. Khazaal *et al.* [21] introduce a fuzzy-MPC scheme to address wind turbines of variable-speed using Inequalities of Matrix approach.

In our manuscript, unlike the work provided in [21] and our previous work in [22], we employ proportional/integral (PI) technique for the optimal power task (instead of P/O technique used in work [22]), a fuzzy technique for adjusting of the DC/DC bidirectional convertor, and a joint of MPC with fuzzy technique (fuzzy-MPC) is provided for the inverter of the grid side. The introduced approach not only ensures the high-level energy conversion capability of the system but also mitigates, as far as possible, alternating of the power to insure reliability of the power plants. The rest of this manuscript is prepared as follows; in section 2 we provide some details about the considered model. Results and simulations are submitted and discussed in section 3. Finally, the work is concluded in section 4.

2. PROPOSED MODEL FOR THE WT CONTROL

The diagram of the complete wind energy scheme is illustrated in Figure 1. This model proposes the employing of various types of algorithms for machine-side/load-side inverter, while the scheme employs an uncontrolled-rectifier for simplicity. This arrangement of joining a fuzzy tech with predictive model tech in the management of the power transferring can create a robust system. Where the MPC part assists the model w.r.t to past-outputs and determines coming up inputs and thus gives system robustness. Fuzzy logic, on the other hand, can deal with the non-linear behavior of the model.

2.1. Proportional-integral control of the blades pitch angle

The benefit of MPPT techniques is to improve wind turbine efficiency. For this purpose, different approaches for optimal power have been created and applied like the incremental conductance method, perturb/observe, and hill climbing approach. Hill climbing schemes or P&O approaches are the commonly utilized tracking algorithms for the MPPT purpose in the wind turbines, e.g., for more details, refer to [23] (and the references therein). In the current work, we employ conventional PI approach to adjust the blades pitch-angle of Figure 1.

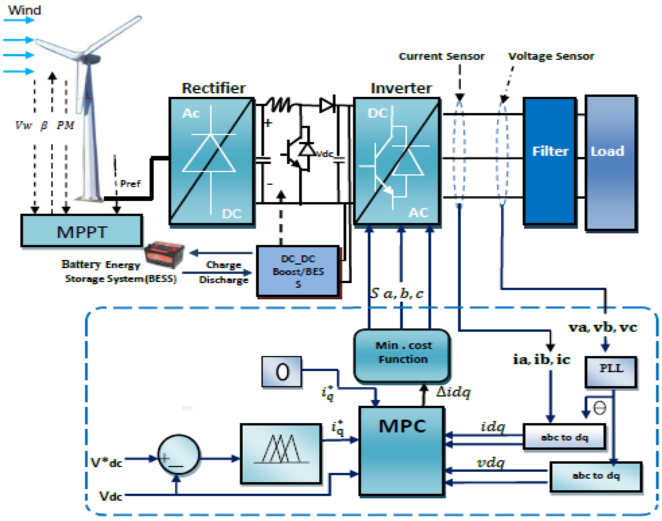

Figure 1. The proposed control scheme for the WT and battery system

According to reference [24], the captured power, i.e., mechanical power P_m, from the wind can be determined as,

$$P_m = 0.5\,\rho\,\pi\,R^2\;C_p\,(\lambda,\beta)\;V_w^3 \tag{1}$$

where, P_m is the extracted wind power, R is the rotor blade radius, ρ = density of the air, V_w is speed of the wind, β is pitch angle, λ is the tip speed ratio, and $C_p\,(\lambda,\beta)$ is the power conversion coefficient and according to our turbine model, can be modeled with the following generic equation,

$$C_p\,(\lambda,\beta) = 0.5\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{-(\frac{21}{\lambda_i})} \tag{2}$$

$$1/\lambda_i = \frac{1}{\lambda_i + 0.08\,\beta} - \frac{0.035}{\beta^3} \tag{3}$$

Consequently, the maximum power point tracking can be determined using the following equation [23]

$$P_{mppt} = 0.5\,\rho\,\pi\,R^2\;C_{opt} \tag{4}$$

here, λ_{opt} is optimal value of tip speed ratio at which the power and the power conversion coefficient are maximums.

2.2. Battery energy-storage system controller

A battery storage device can be utilised to store the excess produced-energy. This storage can be used to supply the load if additional energy is needed. Consequently, a bi_ directional controller is needed to discharge/or charge the battery storage device if there is an overflow/shortage of energy, respectively. The state of battery charging (SOC) percentage information (percentage of the device capacity) can be used to express the quantity of electrochemical energy remained in a battery storage device e.g. see in [25, 26] and the references there in for more details on SOC. A buck-boost operation mode of bi-directional DC controller can be employed for charging/or discharging purpose. In the proposed approach, a system of energy storage is applied to keep DC voltage at a stable level where a fuzzy controller is employed to accomplish this job.

2.3. Controller of load-side inverter

The controller of load-side inverter (LSI) is a current_regulated approach inverter in which current in the direct_axis i_d is used to regulate the voltage of the dc bus while current in the quadrature_axis i_q is applied to control the system reactive power (see Figure 1). The reactive power request is set to zero to confirm unity power factor condition. The controller of load-side inverter is a hybrid scheme produced as a joint of fuzzy algorithm and MPC technique. The key feature of the model predictive approach is using the plant model for the prediction of future performance for some variables within a definite horizon of the model. Figure 2 depicts the flowchart for MPC procedure in which cost function is given as,

$$g = \sum_j^J \lambda_j\,(x_j^* - x_j^P)^2 \tag{5}$$

here, λ_j is the weighting factor, x_j^P is the prediction of the variable x_j, and x_j^* is the reference command. dq_load currents-prediction can be used to adjust the current of LSI and this quantity depends on the dq-converter-voltage components. The Park and Clarke voltage transformation can be expressed, respectively, as follows in (2) and (3),

$$\begin{bmatrix} V_d^j \\ V_q^j \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_\alpha^j \\ V_\beta^j \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} V_\alpha^j \\ V_\beta^j \end{bmatrix} = V_{dc}^* \begin{bmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{7}$$

here, V_α^j and V_β^j are the stationary vectors for voltage within the α and β axis, V_d^j and V_q^j are the dq_axis component vectors of voltage and S_{abc} are the controller switching signals. Euler formula is employed to determine the discrete dq_ currents as follows;

$$i_{gd}^j[\,k+1\,] = \frac{T_s}{L}\left[V_{gd}^j[k] - V_d^j[\,k\,]\right] + \left(1 - \frac{T_s}{L}\right) i_{gd}^j[\,k\,] \tag{8}$$

$$i^{j}_{gq}[k+1] = \frac{T_s}{L}\left[V^{j}_{gq}[k] - V^{j}_{q}[k]\right] + \left(1-\frac{R\,T_s}{L}\right) i^{j}_{gq}[k] \tag{9}$$

Error signals dq-axis load currents $\Delta i^{j}_{gd}[k+1]$ and $\Delta i^{j}_{gq}[k+1]$ are determined as follows;

$$\Delta i^{j}_{gd}[k+1] = \Delta i^{*}_{gd}[k] - \Delta i^{j}_{gd}[k+1] \tag{10}$$

$$\Delta i^{j}_{gq}[k+1] = \Delta i^{*}_{gq}[k] - \Delta i^{j}_{gq}[k+1] \tag{11}$$

The cost function in the prediction procedure can be determined as follows;

$$g^{j} = \left|\Delta i^{j}_{gd}[k+1]\right| + \left|\Delta i^{j}_{gq}[k+1]\right| \tag{12}$$

Now, this cost function could be minimized by choosing the optimum switching signals values. The input reference-current of the model predictive, i.e., i^{*}_{q} can be estimated through the inference of fuzzy logic (see Figure 3) where the fuzzy logic for current control is given in Figure 4 the input/output membership-function given in Figure 5. The associated Inference_Rule for the Fuzzy controller is presented in Table 1.

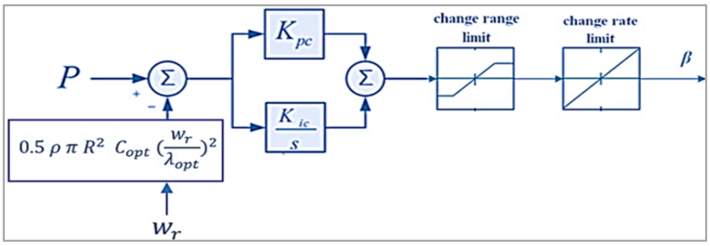

Figure 2. Pitch angle control block diagram

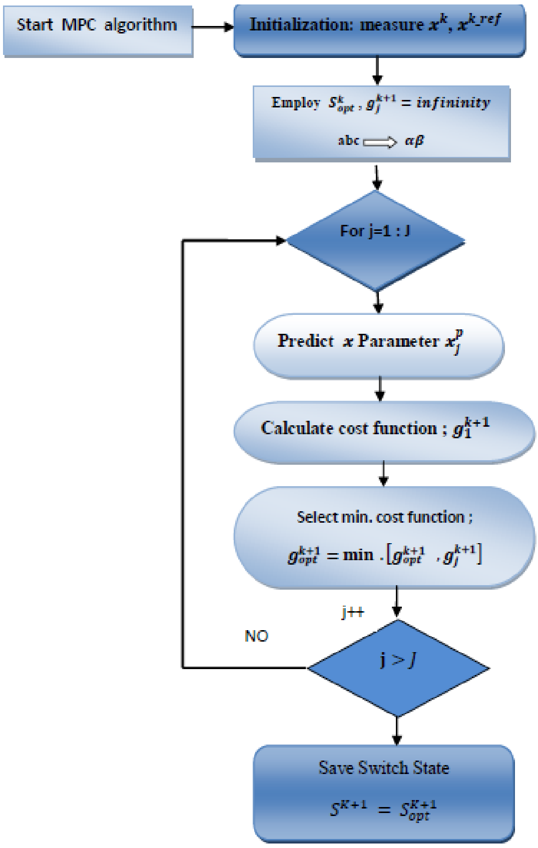

Figure 3. MPC algorithm flowchart

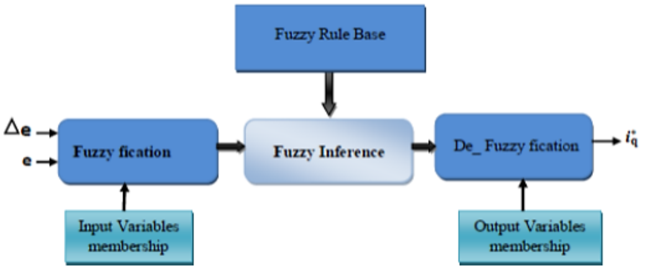

Figure 4. LSI reference current prediction

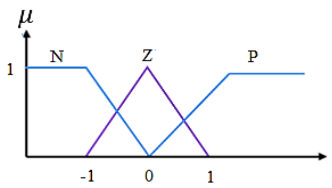

Figure 5. Input/output membership_function of fuzzy technique

Table 1. Fuzzy controller Inference_Rule

e/Δe	N	Z	P
N	N	N	Z
Z	Z	Z	P
P	Z	P	P

3. RESULTS OF THE SIMULATION

System components (the generator, battery, and turbine) are modelled using the Simulink environment of MATLAB package as shown in Figure 6 to investigate the overall performance of the proposed approach. In the simulation study, the parameters of the components for the scheme are set according to Table 2 and the simulation is passed for 4 sec in each situation. The entire simulation results can be put in two parts. First, results for the variable wind-speed case. Second, results for different load case.

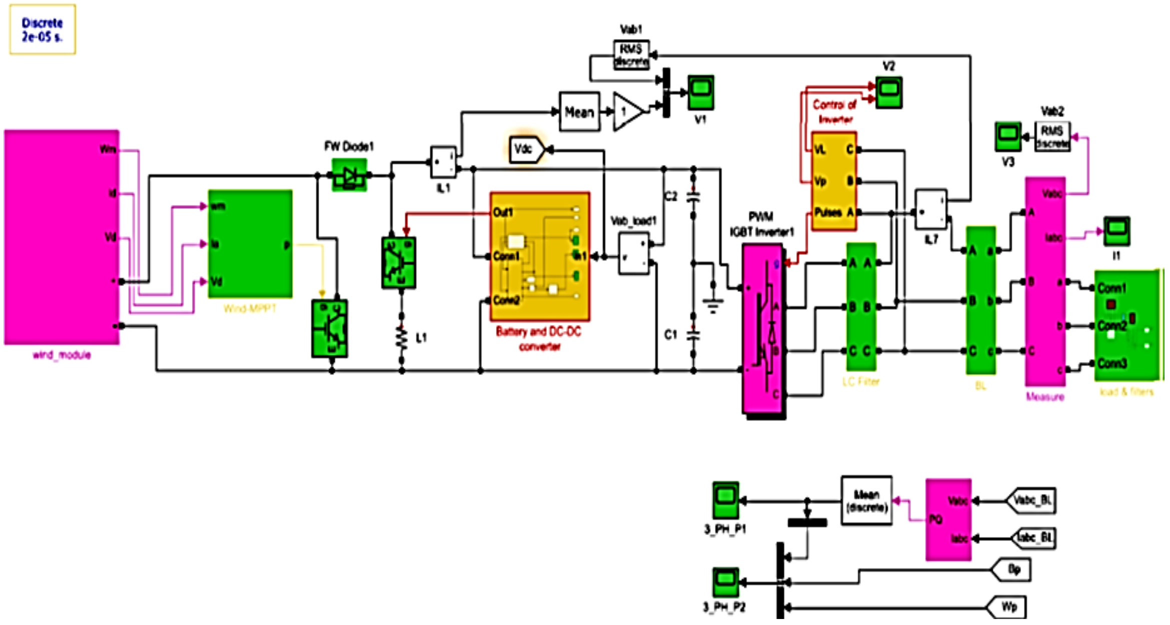

Figure 6. Proposed model block diagram

Table 2. System parameters setting

Parameters	Values
Wind Turbine	
frequency	50Hz
average power	25Kw
voltage	380v
average wind speed	12 m/sec
Direct, Quadrature-axis inductance L_d, L_q	0.435mH
Number of pole-pairs	4
Battery storage system	
Initial SoC	60%
battery capacity	6.5 Ah
nominal voltage	350v

3.1. Machine side controller response

Four various levels of wind speeds are excited at system input in the time interval between 0 sec and 4 sec as shown in Figure 7. The optimal power tracking (turbine rotor-speed response) for the imposed reference parameter is depicted in Figure 8. After a tiny oscillation following the wind speed oscillation, the power-coefficient is kept at the optimum level fast, where it endures around 0.2 sec to move amid two various stable levels.

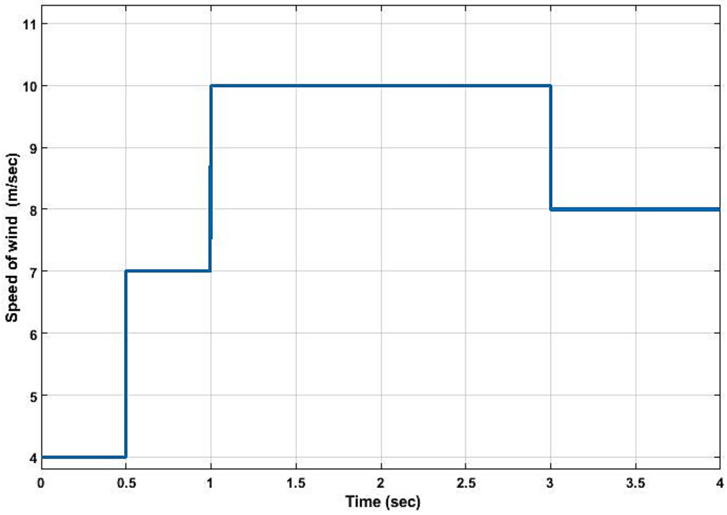

Figure 7. System input excitation (wind speed)

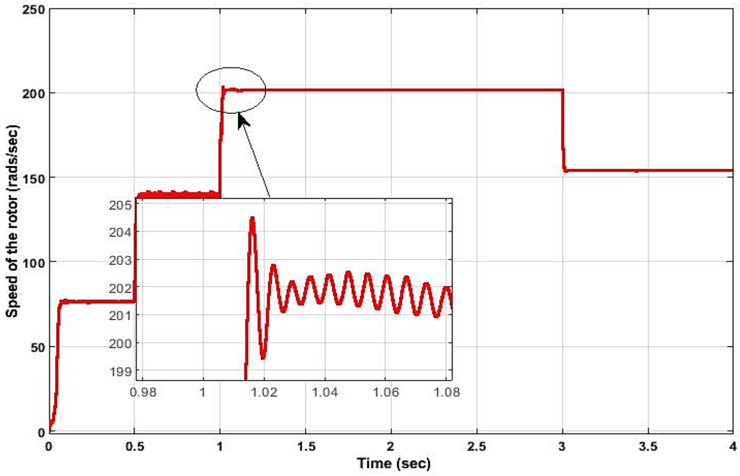

Figure 8. The response of rotor speed for abrupt input excitation

3.2. The response of the DC line bi-directional control

DC_bus voltage V_{dc} is wanted to be around a steady reference point V_{dc}^* (nearly 650v, as shown in Figure 9) which will be adjusted to AC phase voltage of 230v /50Hz at load side via inverter cct. According to the load power demand the bi-directional controller will determine which process of charge or discharge to take place. As shown in Figure 9, in the situation when the created wind power is high and the requested load-power is low, in this case the overflowing power is used to charge the storage device and vice versa. In addition, Figure 10 shows the dc current of through the battery circuit and Figure 11 depicts the percentage variation of energy storage due to charge – discharge process where initial charging state percentage is 60%.

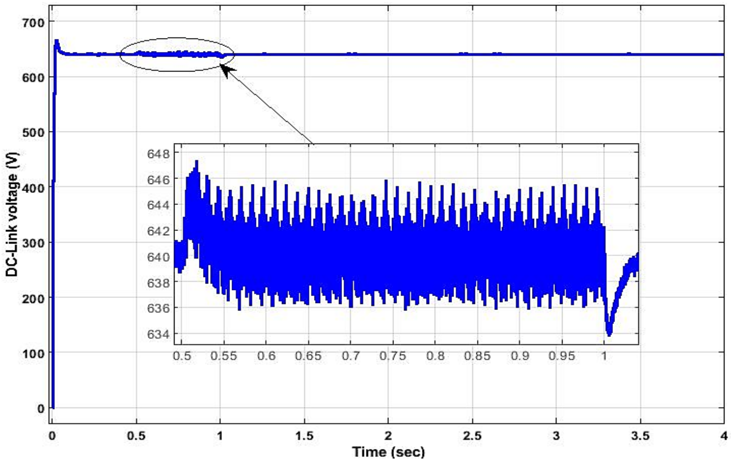

Figure 9. Boosted DC link voltage

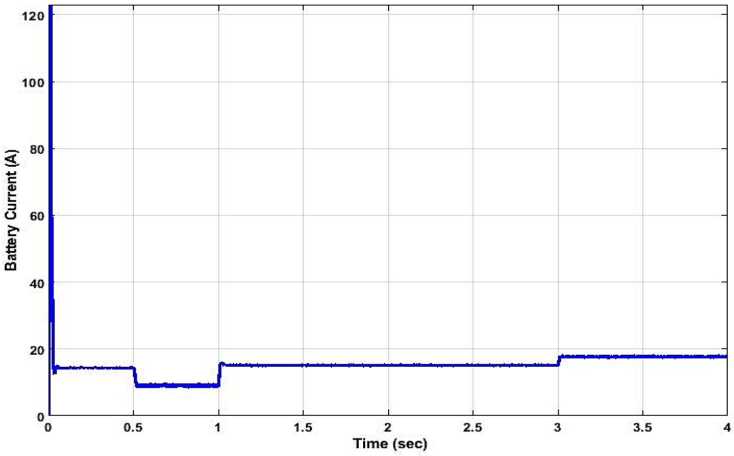

Figure 10. Battery charge/discharge current

3.3. Load side controller response

Along with the previous step-change in wind speed level, the influence of abrupt load change (see Figure 12 at second 3) is inspected simultaneously in order to show the stability of the scheme against environmental fluctuations. Figure 13 shows the change in DC-bus current due to this sudden variation in load current. The simulation is run through two various methods of load_side control, one is our proposed scheme and another one is the traditional PI scheme as a baseline to the proposed scheme performance.

Figure 14 proves that both approaches have a good response versus sudden fluctuations in wind-speed. The figure presents voltage fluctuations w.r.t various wind-speed and load-current. Nevertheless, the proposed model has additional reliability and robustness than the benchmark classical scheme upon all operational region. Besides, our proposed scheme tracks faster at a steady voltage under load fluctuation. When the proposed system undergoes a step change, it provides a key decreasing in overshoot and settling time values (see Table 3). Enhancement in the overshoot response is around 1.1% while the reduction in settling time is around 0.33 msec.

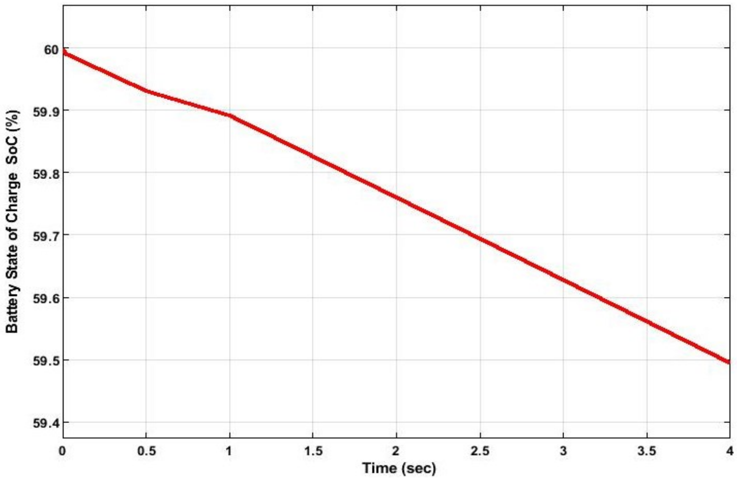

Figure 11. Battery charging state (percentage)

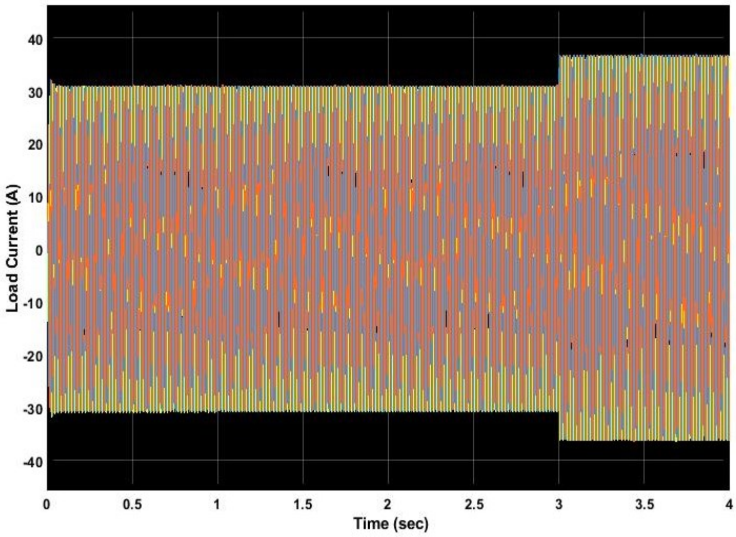

Figure 12. Output load current

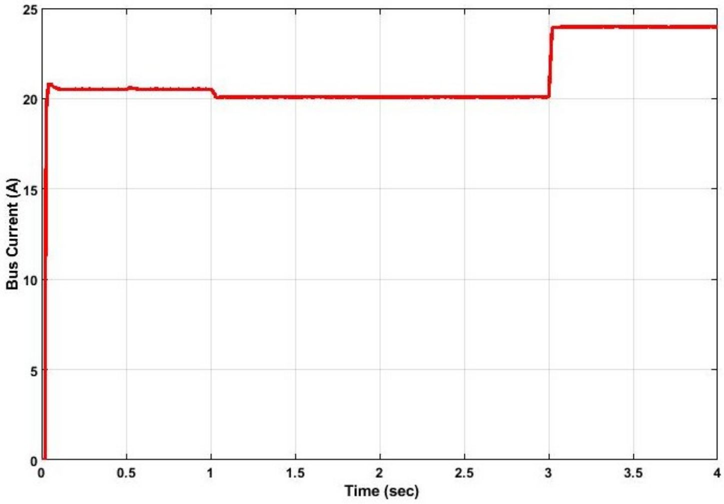

Figure 13. DC–bus current

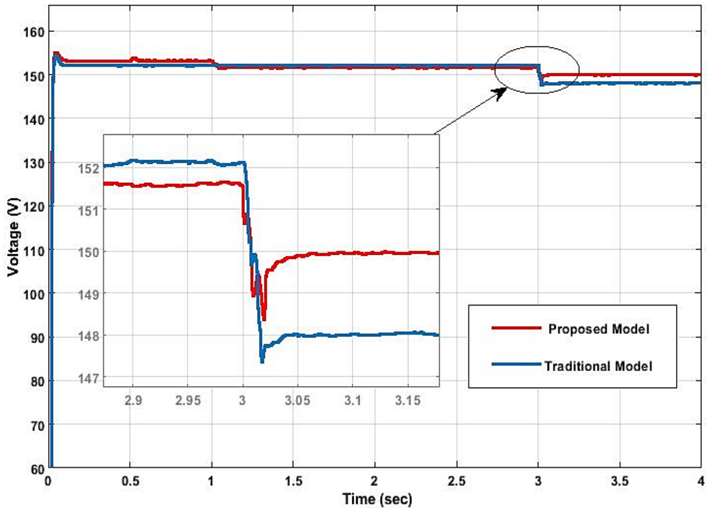

Figure 14. Comparison with the conventional PI approach

Table 3. Response to step input

Metric/technique	Overshoot value (%)	Time of system settling (msec)
Proposed	1.41	0.21
Traditional PI	2.51	0.53

Total harmonic_distortion (THD) of voltage or current signals, on the other hand, is a key quantity beneficial in qualifying the AC waveform quality and this important metric can be determined as (8),

$$\mathrm{THD_v} = \frac{1}{V_1}\sqrt{\sum_{i=2}^{\infty} V_i^2} \times 100\% \tag{8}$$

here, i is the harmonic index and V_1 is the fundamental voltage bin. In this work, the THD measure (Figure 15) introduces a tiny volume of decreasing from 3.7% for the benchmark scheme to 2.55% for our proposed model at 50Hz frequency. It is worth mention here that these limits of THD are almost reasonable according to IEEE standards. In addition, the usage of uncontrolled-rectifier and the passive components in the topology of the proposed scheme results in some high harmonics limits. Consequently, there is a need for using a filter for the machine side to mitigates effects of high harmonics.

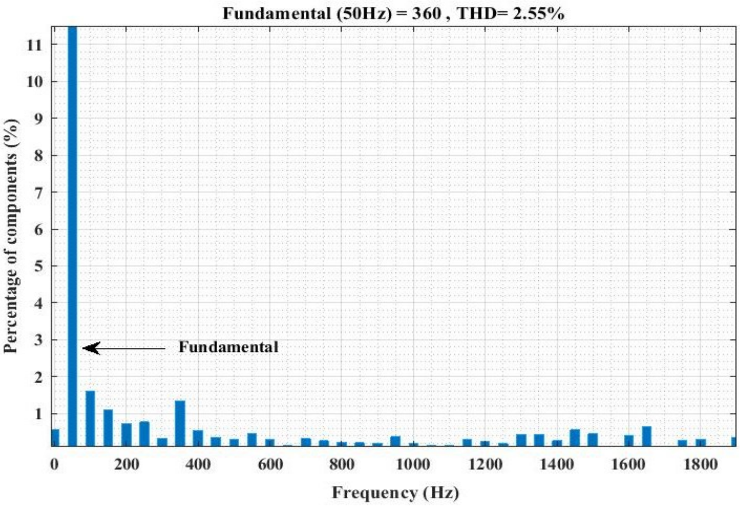

Figure 15. Harmonics performance at 50Hz frequency

4. CONCLUSION

This work introduces a controlling approach that considers of joining of fuzzy technique with model predictive techniques in management of the battery-storage based turbine system. Where the MPC part predicts the model w.r.t to past-readings and determines future inputs and thus gives system robustness. Fuzzy logic, on the other hand, can deal with the non-linear behaviour of the model. Simulation output results verify the efficiency of the proposed approach in pursuing the required recommended metrics in terms of overshoot and settling time.

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