A Hybrid Control Strategy for PMSG-based Standalone Wind Turbines with BESS

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Abstract. Energy conversion efficiency and power quality are both two key objectives of control schemes in wind energy conversion systems (WECS). These two tasks are hard to trade off and contradictory since improving the conversion-efficiency may boost fluctuation of output power as well. This paper suggests a hybrid control strategy for variable speed PMGS with Battery energy storage system to provide consistent power and meet variable load demands. In the suggested scheme, Fuzzy logic is combined with Model Predictive Control (MPC) to capture the merits of these two different methods. The proposed controller (F_MPC) could improve wind turbine performance and provide power reliability. Simulation results prove that, in comparison with traditional PI model, the proposed topology can achieve benefits in terms of step response (overshoot), frequency deviation, and total harmonic distortion (THD) of almost 1.2%, 4.2%, and 1.24% respectively.

Keywords. Fuzzy logic; model predictive; Battery Energy Storage Perturb & Observing; cost function.

1. Introduction

With growing load requirements and global warming, energy of wind has become one of the important renewable energy technologies to employ and develop [1,2]. In this regard, wind turbine (WT) control schemes have been considered for a number of decades. However, the aspect of control strategies is still open problem for researchers. In general, controller of WTs is one of two parts according to the main objective of the controller. In maximum power point tracking (MPPT) algorithms, the aim is to achieve efficient or optimal energy of wind conversion. While in WTs operate above nominal wind speed power quality is the main control aim, and of course it is important to consider efficiency of energy conversion [3,4]. In addition, the capability of Fault Ride Through (FRT) is one of the key challenging demands in regulations of existing network to maintain synchronous generator function when a disturbance occurs. In these points, power quality (fluctuation reduction) and power conversion efficiency have been considered in-depth separately [5,6]. Nevertheless, enhancing power quality without devices for energy storage may result in efficiency loss. Although many power smoothing methods based on storage devices. In [4] a new MPPT regime via fuzzy inference system (FIS) was suggested to consider the objectives mentioned previously i.e., enhancing energy efficiency and power quality.

Other modern control paradigms, such as nonlinear control [7], robust controller [8] and adaptive controller [9] are also proposed for WT systems. Zhang et al. in [9] suggested an adaptive MPPT approach using reinforcement of a network based learning to address the variations of system environment. MPC approach is usually used to handle linear or nonlinear constraints multi objective optimizations. In [10-13], MPC has been utilized for generator side controller (GSC). In [14] MPC has been employed for wind/battery hybrid controller. Evans et al. in [15] applied MPC for conversion efficiency and Mechanical load. In [16,17] MPC is considered for multi objective control. MPC is employed in [18,19] to address drive train loads and energy conversion. In [20] a terminal quality constraint is used to insure the stability of MPC model with retreating horizon. Reference [19] introduced a MPC approach in which the linear models are modified according to condition of wind speed as state space linearization is necessary for MPC modelling. Reference
[21] suggested a tuning scheme via the calculation of tables of sensitivity. Variable wind environments are used to modify weights in reference [22] by classifying various wind speed conditions. Bououden et al. in [23] addressed a fuzzy logic based MPC scheme to enhance system efficiency and control performance. Authors in [24] provided a fuzzy model-predictive model to control a variable WT via Linear Matrix- Inequalities method. In this paper, different from the study introduced in [24], we consider P&O approach for the MPPT objective, fuzzy logic control for the bidirectional DC-DC converter, and fuzzy-model predictive hybrid approach for the load side inverter. The suggested model not only achieves efficiency of the energy conversion at a high level, but also suppresses fluctuations of power as much as possible to achieve power systems reliability. The remainder of this work is organized as follows; section 2 gives details of the proposed model. Simulation studies and results are introduced and discussed in Section 3. Finally, section 4 concludes the study.

2. Hybrid Control model

Fig. 1 below depicts the schematic diagram of the entire wind energy system. We suggest the using of three controllers for pitch angle, dc-dc converter, and load side inverter, respectively, and for the sake of simplicity, we propose uncontrolled rectifier.

![Diagram of WT and BSEE Control model](image)

**Figure 1.** WT and BSEE Control model

2.1. Tracking of Maximum Power Point

MPPT approach is used to enhance the efficiency of the wind turbine. There are various algorithms for MPPT have been introduced and implemented such as Perturb and Observe (P&O), hill climbing method, and Incremental Conductance method. Due to their simplicity, P&O algorithms or hill climbing schemes are the usually utilized tracking approaches for the capture of maximum-power from wind source, e.g. see
[25], [26] and the references therein for more details. In the present study we employ P&O algorithm in pitch angle controller of Fig.1.

2.2. Storage of Battery Energy

The excess produced energy can be stored in a storage device (Battery), where this energy can be employed to provide the load when energy is demanded. Therefore, a bi-directional converter is required to discharge and/or charge the storage device in case of deficit and/or excess of energy. The electrochemical energy quantity left in a storage device can be expressed as a percentage of the device capacity or the state of charge (SOC) information. Bi-directional DC-DC converter can be used in charging/discharging (buck/boost) operation modes. Our proposed model depends on battery energy storage system (BESS) to maintain dc-bus voltage at constant value. Fuzzy logic (FL) is utilized to achieve this task, see reference [27] for more details on SOC.

2.3. Load Side Inverter

As shown in Fig. 1, the Load side inverter (LSI) is a current regulated inverter with the direct-axis current is used to adjust the dc-bus voltage and quadrature-axis current is used to adjust the reactive-power. To ensure unity power-factor operation, we set the reactive-power demand to zero. LSI is a hybrid control scheme from a combination of fuzzy logic with MPC. Model predictive is an useful approach that key feature is using the model of the plant for the future behaviour prediction of the some variables over a definite prediction horizon. MPC algorithm flow-chart is given in fig. 2, where cost function can be expressed as follows,

\[ g = \sum_{j} \lambda_j (x_j^* - x_j^p)^2 \]  

(1)

given that, \( \lambda_j \) is weighting-factor, \( x_j^* \) is the reference command and \( x_j^p \) is the predicted value for variable \( x_j \). The current of LSI can be modified using dq_load currents prediction which are in turns, relay on the dq-converter-voltage components . Equations (2) and (3) are, respectively, the Park and Clarke transformation,

\[
\begin{bmatrix}
V_d^j \\
V_q^j
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
V_a^j \\
V_\beta^j
\end{bmatrix}
\]

(2)

\[
\begin{bmatrix}
V_a^j \\
V_\beta^j
\end{bmatrix} = V_{dc}^j
\begin{bmatrix}
\frac{2}{3} & \frac{1}{3} & \frac{-1}{3} \\
0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}}
\end{bmatrix}
\begin{bmatrix}
S_a \\
S_b \\
S_c
\end{bmatrix}
\]

(3)

where \( V_d^j \) and \( V_q^j \) are the dq-axis component voltage-vectors, \( V_a^j \) and \( V_\beta^j \) are the stationary voltage-vectors in the \( \alpha \) and \( \beta \) axis, and \( S_{abc} \) are the switching-signals of the controller. The discrete dq_currents can be formulated using Euler method,
Figure 2. Model Predictive Control (MPC) progressing steps.

\[ i_{gd}[k+1] = \frac{T_s}{L} \left[ v_{gd}[k] - v_d[k] \right] + \left( 1 - \frac{T_s}{L} \right) i_{gd}[k] \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3) \]

\[ i_{gq}[k+1] = \frac{T_s}{L} \left[ v_{gq}[k] - v_q[k] \right] + \left( 1 - \frac{R T_s}{L} \right) i_{gq}[k] \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4) \]

Now, error dq-axis load currents \( \Delta i_{gd}[k+1] \) and \( \Delta i_{gq}[k+1] \) can be as calculated follows,

\[ \Delta i_{gd}[k+1] = \Delta i_{gd}[k] - \Delta i_{gd}[k+1] \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5) \]

\[ \Delta i_{gq}[k+1] = \Delta i_{gq}[k] - \Delta i_{gq}[k+1] \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (6) \]

While the cost function can be given as follows,

\[ g^1 = \left| \Delta i_{gd}[k+1] \right| + \left| \Delta i_{gq}[k+1] \right| \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (7) \]
Then by selection the optimal values of the switching-signals the cost function can be minimized. As depicted in fig. 1, the MPC input reference current $i_{q}^{r}$ can be predicted via a fuzzy logic inference with input/output membership function shown below.

![Fuzzy logic controller for reference current prediction of LSI, fig.1](image)

Figure 3. Fuzzy logic controller for reference current prediction of LSI, fig.1

![Membership Function of fuzzy controller for the input/output variables Table 1 Fuzzy controller rule base](image)

Figure 4. Membership Function of fuzzy controller for the input/output variables Table 1 Fuzzy controller rule base

| Table 1. Inference Rule base. |
|-----------------------------|
| e/Δe | N | Z | P |
| N   | N | N | Z |
| Z   | Z | Z | P |
| P   | Z | P | P |

3. **Simulation Results**

MATLAB-Simulink environment is utilized in the implementation of the proposed hybrid control system. Table 2 gives the parameters and specifications of the system for simulation study. Where all components i.e., the generator, turbine, and battery are modelled, accurately, in MATLAB (see Fig.5 below) in order to predict their practical features. The test is run on 4 seconds for all cases. Two main sections can be noticed in the entire simulation. First, performance under Variable wind speed conditions (see Fig.10). Second, performance under different load conditions.

| Table 2. Specifications and Parameters of the wind turbine, Battery and PMSG used in the Simulation |
|-------------------------------------------------------------------------------------------------|
| | |
| | |
| | |
| Parameter | Rating value |
|-----------|--------------|
| **Wind-energy conversion system (WECS)** | |
| voltage | 380v |
| nominal power | 25Kw |
| frequency | 50Hz |
| nominal wind speed | 12 m/sec |
| Number of pole-pairs | 4 |
| Direct, Quadrature-axis inductance $L_d, L_q$ | 0.435mH |
| **Battery-Energy storage system (BESS)** | |
| nominal voltage | 350v |
| battery capacity | 6.5 Ah |
| Initial SoC | 60% |

3.1. **Response of the Machine Side Controller (P&O)**

Fig.6 shows system input variations (four different wind speeds) in the interval between 0 and 4 sec. The consequence response of the turbine rotor speed is shown in Fig.7 which depicts the peak power tracking of the applied MPPT controller for the reference value. After a small fluctuating (according to the wind speed fluctuating), the power coefficient would back to the optimal value quickly and it takes less than 0.2sec to switch between two different stable states.

**Figure 5.** Diagram of the proposed model.
3.2 Response of the bi-directional DC/DC BESS controller (Fuzzy)

From Fig.9, in this case when the power generated from wind is high and the load power demand is low the excess generated power is utilized to charge the BESS.

The voltage over the DC-bus i.e., $V_{dc}$, is desired to be within constant reference $V_{dc}^*$ (around 650v), and after inverting this voltage, load side value will be adjusted to 230v/50Hz.

3.3 Response of the Load Side Controller (F_MPC)

The impact of sudden load change is investigated along with wind speed variation (Step change) in order to prove stability of the system. The simulation is carried out using two different types of load-side controllers (LSC) one is the proposed F_MPC design and another is the conventional PI model as a
benchmark to the F_MPC system performance. Both schemes have a high accuracy response against step change in wind speed as shown in Fig. 13 & 14 that present the output voltage variation with respect to the different load and wind speed. However, F_MPC is more reliable and robust than the baseline traditional controller across all points of operation. In addition, the proposed model can track sooner with a more stable output voltage under disturbance of the load. In terms of performance sensitivity, F_MPC introduces a key reduction in settling time and overshoot values when the system is subjected to step excitation (see fig.13 and Table 3). Overshoot response improvement is about 1.2% and Settling Time reduction is 0.32msec.
Table 3. Step response.

| metric  | Overshoot (%) | Settling Time (msec) |
|---------|---------------|---------------------|
| F_MPC   | 1.31          | 0.19                |
| PI      | 2.52          | 0.54                |

Figure 13. Baseline (Traditional PI) controller vs. F_MPC voltage comparison.

Figure 14. Output load voltage.

An important quantity useful in determining AC- signal quality is the total harmonic distortion (THD) for load current or voltage waveform and this metric can be calculated by considering the following formula,

\[
\text{THD}_v = \frac{1}{V_1} \sqrt{\sum_{i=2}^{\infty} V_i^2} \times 100\% \quad \ldots \quad \ldots \quad \ldots \quad (8)
\]

where, \( V_1 \) is the fundamental voltage component and \( i \) is the harmonic index.

This measure can be realized through Fast Fourier Transform (FFT) tool of analysis in Powergui-block of SIMULINK environment. In this study, THD metric presents a small amount of reduction from 4.01% for the baseline model to 2.75% for the proposed one at 50Hz fundamental frequency which is almost acceptable within the allowed limits of IEEEE standards. It is worth mentioning here that because of the passive elements and uncontrolled-rectifier proposed in this topology, there will be some high-harmonics restrictions that required using of passive filter at the PMGS’s side to minimize the impact of these harmonics. Furthermore, fig.15 depicts the frequency variation of both schemes. It is obvious that for the proposed system, frequency values are diverse within tolerable limit of fundamental 50Hz in the range of ±1.2% compared with ±5.4% for the baseline model.
Figure 15. THD Analysis of both models at 50Hz for F_MPC

Figure 16. THD Analysis of both models at 50Hz for IP model

Figure 17. Load frequency variation for the F_MPC compared to PI traditional benchmark controller.

Conclusion

In this study we have introduced a hybrid control scheme to address the combination of fuzzy logic and model predictive (F_MPC) in controlling standalone WESS with BESS. Where fuzzy logic can handle non-linear behaviour of the system and the MPC predict the model according to past-measurements and calculated future inputs which provides system robustness. Obtained results prove the effectiveness of the introduced model in tracking the desired reference parameters (fast response) with minimum overshoot and settling time.
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