Emulation of Large Wind Turbines Aerodynamics on Lab Scale DFIG Machines

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***Abstract*—Wind turbine designs must be evaluated for performance, power characteristics, and behavior under grid disturbances such as faults and unbalance before field deployment. Conventional simulations using empirical relations to represent the $C_p - \lambda$ curve, although useful, may not fully capture real-system aerodynamic modeling under varying pitch angles. To address this, we develop a hardware wind turbine emulator on an 11 kW squirrel-cage induction machine (SCIM) coupled to a doubly fed induction generator (DFIG), integrating pitch control and a maximum power point tracking (MPPT) algorithm. 0.75 MW and 5 MW reference turbines from National Renewable Energy Laboratory (NREL) are emulated under time-varying wind profiles using aerodynamic blade modeling to obtain realistic turbine characteristics. The Blade element momentum (BEM) method is used to do the detailed aerodynamic modeling and obtain the $C_p - \lambda$ curve for different pitch angles. Open source software Qblade community edition is used to obtain $C_p - \lambda$ curve.**

***Index Terms*—Wind turbine emulator, SCIM, DFIG, MPPT, pitch control, vector control**

I. Introduction

Wind power extraction began with simple thrust-based turbines and evolved into more efficient aerodynamic designs. The advent of power electronics enabled variable speed turbines using Permanent Magnet Synchronous Motor (PMSM) or doubly fed induction generator (DFIG) and bi-directional converters to maximize power extraction. They can operate in generating mode over a large speed ranges. However, these systems require complex control algorithms which should be validated thoroughly before deploying it in actual turbine. To address this, many studies have focused on laboratory emulation of variable speed turbines.

A 20 kW separately excited DC motor controlled by a microcontroller is used in [1] to emulate the mechanical characteristics of a wind turbine, based on a two-mass model solved numerically. In [2], a dual DSP-based emulator with a DC machine coupled to a squirrel-cage induction generator is implemented to study the steady-state behavior of fixed-speed wind turbines. A type-3 wind turbine is emulated in [3] using a DC motor and DFIG, incorporating the (C_p–λ) torque–speed characteristics, field-oriented control, maximum power point tracking (MPPT) and pitch control integration. A 3 kW DC machine as prime mover coupled with a DFIG is employed in [15] to emulate a fixed-pitch wind turbine, where expression of C_p as a function of λ is obtained by curve fitting.

Although inertia emulation is not included in [2] and [3], the limitation is addressed in [4] by adding "inertia compensation torque" to the torque reference of the DC machine; however, this method cannot emulate turbines with inertia more than twice that of the laboratory machine. To overcome this constraint, a 2-DOF control system using an induction machine and DFIG, both under field-oriented control, is proposed in [5]. A wind turbine emulator with supervisory control and data acquisition (SCADA) for research and training is developed in [6], using an induction machine coupled to a permanent magnet synchronous generator (PMSG) connected to the grid via a back-to-back converter. A 5 kW scaled prototype of a 2.5 MW induction generator is presented in [7], designed so that its transient response to step inputs matches that of the full-scale machine, and the associated scaling methodology is detailed. A hardware-in-the-loop (HIL) based approach to emulate a wind turbine generating system (WTGS) is described in [16], where a DC machine is coupled with a PMSG, hardware measurements are exchanged with a real-time simulator that returns the corresponding command signals.

The emulators reviewed utilize empirical relations to represent the $C_p - \lambda$ curve, which may not fully capture real-system aerodynamic modeling under varying pitch angles. In this paper, Open source Qblade community edition software with the Blade element momentum (BEM) method is used to do the detailed aerodynamic modeling and obtain the $C_p - \lambda$ curve for different pitch angles. The main contributions of this paper are: the development of a laboratory-scale squirrel-cage induction machine (SCIM) coupled–DFIG hardware platform for grid-connected wind turbine studies, the modeling of electrical, mechanical, and aerodynamic subsystems to emulate 0.75MW and 5MW NREL reference turbines, and the implementation of an integrated pitch control and MPPT scheme on this platform. A complete real-time wind turbine emulator architecture, based on a modular multi-microcontroller setup, is realized and its performance is validated experimentally.

II. Wind Turbine Emulator Development

Fig. 1 shows the simplified diagram of laboratory setup and its connection to the three phase 415v 50Hz grid. The SCIM is mechanically coupled with the DFIG, where SCIM behaves as a prime mover, emulating the wind-turbine. Fig 2 and Fig. 3 gives the detailed schematic diagram of the power electronic drive connected with SCIM and DFIG respectively. Table I gives the rating of laboratory machines.

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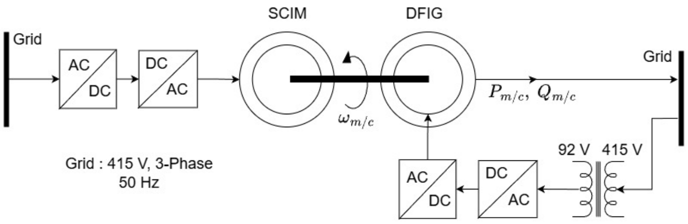

Fig. 1: Simplified diagram of laboratory setup

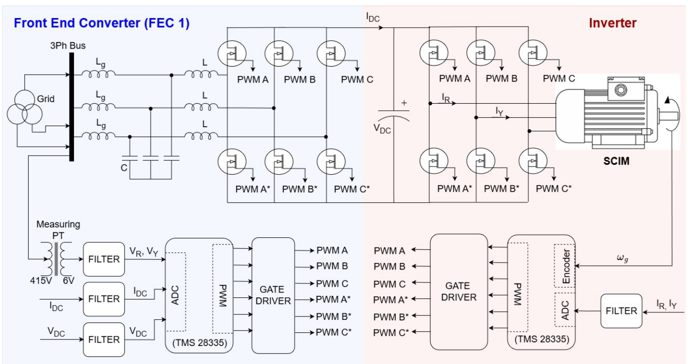

Fig. 2: SCIM drive circuit schematic

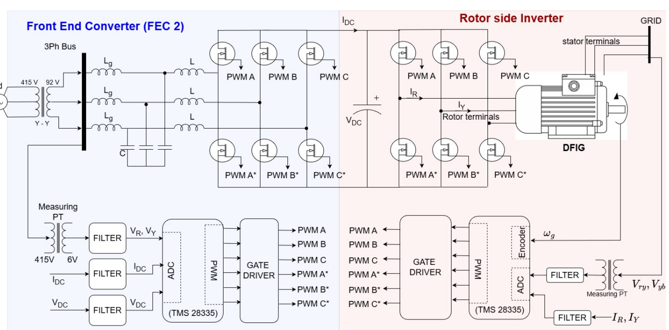

Fig. 3: DFIG drive circuit schematic

TABLE I: Lab DFIG parameters

Lab DFIG parameters	
Rated voltage (R.M.S line-line)	440V
Rated generator speed	1500 rpm
Rated line current (R.M.S)	22A
Generator efficiency	90%
Power factor	0.8
Connection	star
Inertia of SCIM-DFIG set	2.1 kgm^2

A. Modeling of wind turbine

The modelling techniques for Wind Turbine Generating System (WTGS) are well developed [12]. Here a concise description of models used for laboratory setup to emulate the 0.75MW and 5 MW reference wind turbine designs developed by NREL [9] is provided.

B. Aerodynamic modeling

Aerodynamic model characterizes the turbine's aerodynamic behavior and calculates the mechanical power (P_{wind}) extracted from the wind as a function of the incoming wind speed (V_∞), area swept (A) by the turbine and air density (ρ). The generated aero-dynamic torque is given by

$$P_{wind} = \frac{1}{2}\rho A {V_\infty}^3 C_p \tag{1}$$

where, C_p is the power coefficient and depends on the tip speed ratio (λ) and the pitch angle (β) of the blades. The expression of C_p as a function of (β and λ) is obtained by carrying out the detailed aero-dynamic modeling of wind turbine blades in Open source Qblade community edition software using Blade element momentum (BEM) method, at different wind speeds and pitch angles. As a result, C_p is stored as a two-dimentional array in the flash memory of microcontroller.

C. Drive Train Modeling

The two mass model of wind turbine is most commonly used for simulation and emulation purposes [4]. The differential equations governing its dynamics are given by,

$$\begin{aligned}
&J_r\dot{\omega}_r + (B_r + D_r)\omega_r - \left(\frac{D_r}{n_x}\right)\omega_g + K_r\Delta\theta - T_a = 0,\\
&J_g\dot{\omega}_g - \left(\frac{D_r}{n_x}\right)\omega_r + \left(B_g + \frac{D_r}{n_x^2}\right)\omega_g - \left(\frac{K_r}{n_x}\right)\Delta\theta + T_g = 0,\\
&\Delta\dot{\theta} = \omega_r - \frac{\omega_g}{n_x}
\end{aligned} \tag{2}$$

The complete mechanical model of wind turbine can be obtained by integrating the Drive train model and the aero-dynamic model as shown in Fig.4. The parameters of NREL 0.75MW and 5MW reference wind turbine models are taken from [9] for emulation which are validated from field measurements.

III. Emulation Strategy

Fig.5 shows the block diagram of the emulation strategy. Here, the SCIM acts as a prime mover to emulate a wind turbine. The model machine takes wind speed profiles and pitch angle ($V_\infty,\ \beta$) as inputs and gives the computed generator shaft speed (ω_g) as output. The goal of emulation is to make the shaft speed of the SCIM (Ω_r) track the reference turbine's output (ω_g), in Per Unit basis, for the given ($V_\infty,\ \beta$). The SCIM controller needs to be designed to achieve the above objective. τ_g is the counter torque produced by the generator which can be measured using torque sensor. In the present work, need of torque sensor is eliminated by calculating τ_g as follows:

$$\tau_g = \frac{P_g}{\Omega_r * (1-s)}, s = operating\ slip \tag{3}$$

The input β to the aero-dynamic model is generated by the pitch controller. On the generation side, the goal is to ensure that the active power injected into the grid by the laboratory DFIG machine tracks the reference power generated by the MPPT algorithm of the model machine on Per Unit basis. DFIG controller should be designed to achieve this objective. In this paper, 1pu on laboratory 5kW base is taken same as 1pu of the reference wind turbine rating.

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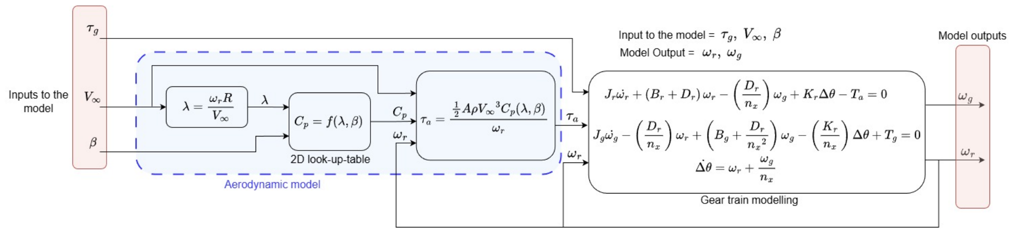

Fig. 4: Complete mechanical model of wind turbine

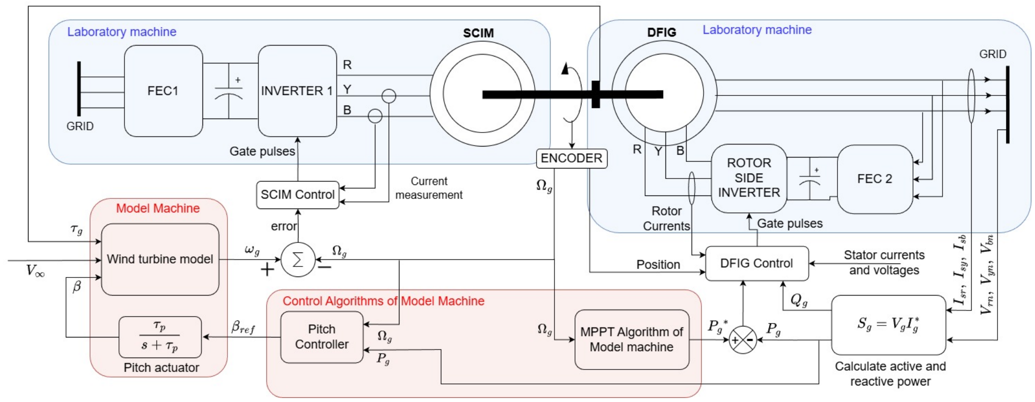

Fig. 5: Block diagram of Emulation strategy. (All the quantities are in PU)

A. Maximum Power Point Tracking Algorithm

The operating point of WTGS is determined by the intersection of the power-speed characteristics of the wind turbine and the DFIG. Therefore, the DFIG is controlled to have the power-speed characteristics as shown in Fig.6, ensuring that the operating point consistently aligns with maximum power. The power speed curve of the turbine is plotted for a pitch angle of zero degrees, at which we have the most optimal value of the ($C_{p,max}$). The equation of MPPT characteristics

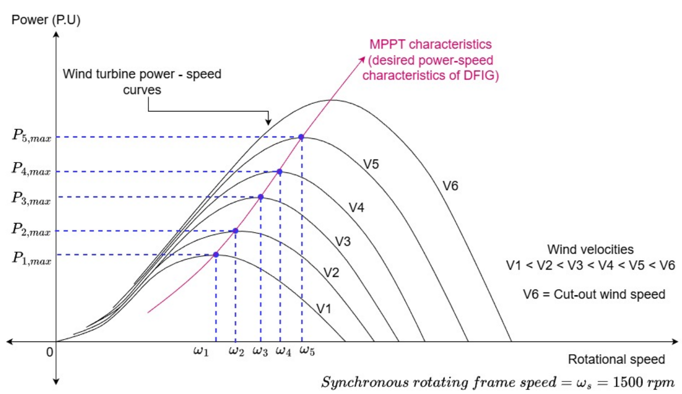

Fig. 6: MPPT characteristics implemented on DFIG

can be derived by considering (1). For a given wind speed (V_∞), the maximum power point occurs when the tip speed ratio (λ) is at its optimal value (λ_{opt}) and the power coefficient (C_p) reaches its maximum ($C_{p,\max}$). Let (P_{MP}) represent the maximum power that can be extracted from the wind at V_∞.

$$P_{MP} = \frac{1}{2}\rho A(V_\infty)^3 C_{p,max}$$

$$But,\ V_\infty = \frac{\omega_g R}{n_x \lambda_{\text{opt}}} \implies P_{MP} = \frac{1}{2}\rho A C_{p,\max}\left(\frac{\omega_g R}{n_x \lambda_{\text{opt}}}\right)^3$$

$$P_{MP} = K_{MPPT} * \omega_g^3;\ K_{MPPT} = \frac{1}{2}\rho A C_{p,\max}\left(\frac{R}{n_x \lambda_{\text{opt}}}\right)^3 \tag{4}$$

Therefore, in order to operate at Maximum power point, the active power injected into the grid by the DFIG should be a function of measured generator speed, as given in (4).

B. Pitch controller

Pitch control is utilized to regulate the aerodynamic torque during periods of increased wind speeds or under light loading conditions. For variable speed wind turbines operating below their rated rotational speed, the pitch angle is maintained at a constant (optimum) value, ensuring maximum torque generation at that specific wind speed. At higher wind speeds or at increased rotational speeds of the turbine, the pitch angle of the blades is increased to reduce the generated aerodynamic torque and the turbine operates at nearly constant speed, delivering constant power into the grid. This is illustrated in Fig.7 There are different methods available to implement the pitch control [11]. Here, a rule-based fuzzy logic controller is implemented, which senses the rotor's speed and accordingly varies the pitch angle. Corresponding flow chart is given in Fig.8 executing at 250ms time step.

C. Vector control of SCIM and DFIG in discrete domain

Field oriented control is implemented on SCIM and DFIG machines to achieve the purpose of reference speed tracking and reference power tracking respectively. The algorithms for

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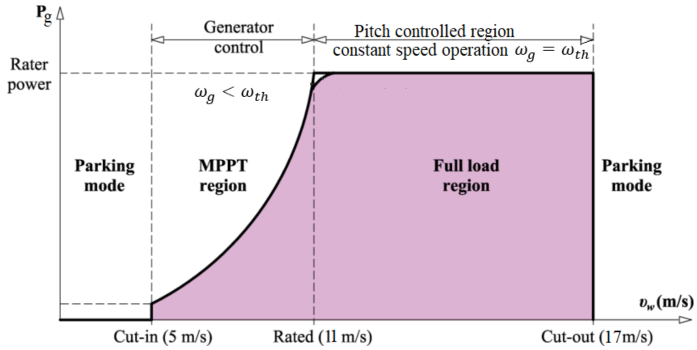


Fig. 7: Power vs wind-speed characteristics of a variable speed wind turbine, taken from [13]

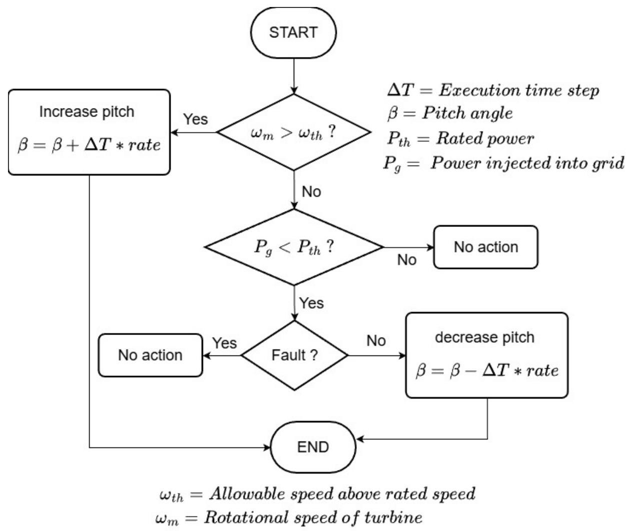
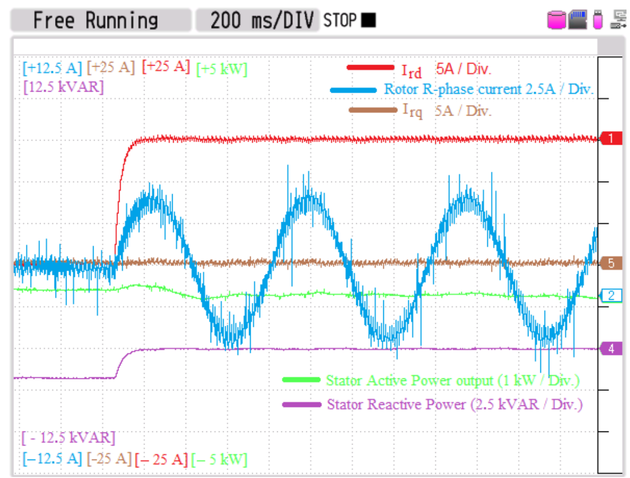


Fig. 8: Flow chart demonstrating the pitch control. Algorithm executed at time step of $\Delta T = 250\ ms$

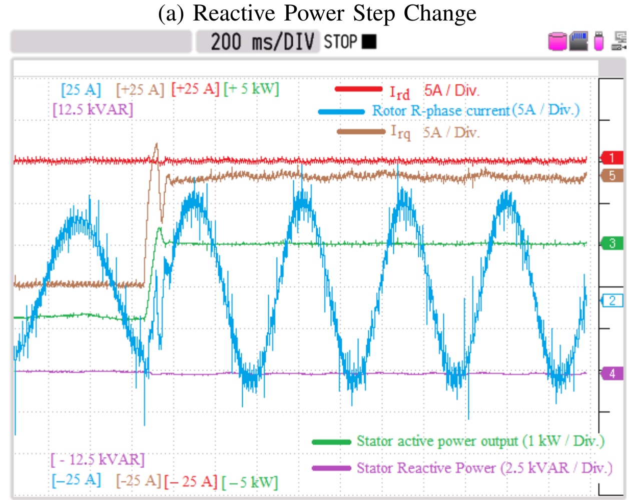
flux position observers are given in [14]. The approach to design the controllers in discrete time domain is discussed in [10].

D. Hardware implementation results

Fig. 9 shows the results of implementing vector control on DFIG running at 1458rpm. In Fig.9a, $I_{rd,ref}$ is increased from 0 to 15A in a step manner and $I_{rq,ref}$ = 0. We can see that only reactive power consumed from grid is changed. The active power injected into the grid is nearly zero. In Fig.9b, $I_{rd,ref}$ is kept constant at 15A and P_{ref} is increased from 0 to 1000W in step manner. Note that only I_{rq} is changed. I_{rd} remains unchanged and tracks $I_{rd,ref}$. Fig.10 shows the results of emulating 0.75 MW and 5 MW wind turbines for a step change in wind speed input. the values of different quantities at the bottom most horizontal line are: Wind speed 5.5 m/s, Active power -4 kW, Rotation speed of generator 100 rad/second. The wind speed is given a step increase from 8.5 to 10m/s for both the turbines (5MW and 0.75 MW). The rotational speed changed from 130 rad/sec to 160 rad/sec. The active power injected into the grid at 8.5 m/s wind speed is 2.45kW = 0.49 PU = 2.45MW for 5 MW turbine and 0.3675MW for 0.75 MW turbine. It can be observed that the 0.75MW turbine reaches steady state power quicker than the 5MW wind turbine demonstrating the effectiveness of the developed emulator. Fig.11 shows the response of the 0.75MW and 5 MW wind turbine emulations subjected to a time-varying wind speed profile based on the Weibull probability distribution. It can be observed that the turbine power nicely tracks the MPPT generated reference.



(a) Reactive Power Step Change



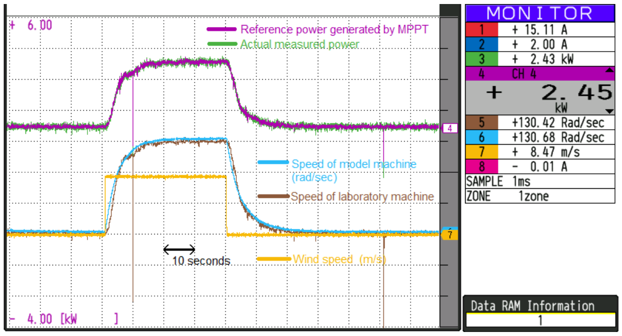
(b) Real Power Step Change

Fig. 9: Controlling active and reactive power of DFIG

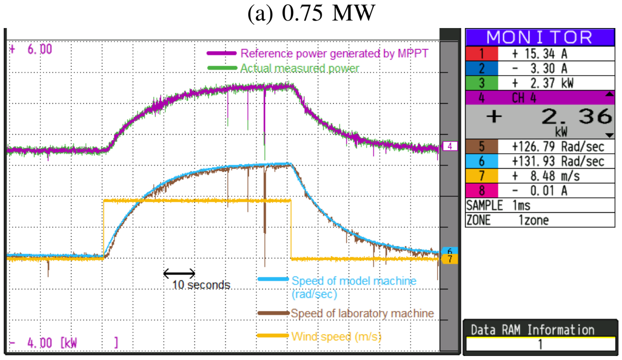
From the above results it can be observed that the steady state characteristics of the large wind turbines are very well captured by the proposed approach. Validation of different control design choices and transient characteristics under faulted conditions is being considered for future work.

IV. Conclusion

A laboratory-scale wind turbine emulator based on an 11 kW SCIM–DFIG set has been developed and experimentally validated. The setup reproduces the behavior of NREL 0.75 MW and 5 MW reference turbines under time-varying wind profiles by combining detailed electrical, mechanical and aerodynamic modeling with an integrated pitch control and MPPT scheme. The Blade element momentum (BEM)

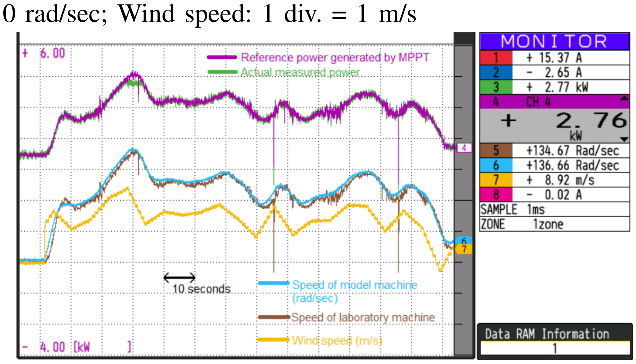


(a) 0.75 MW

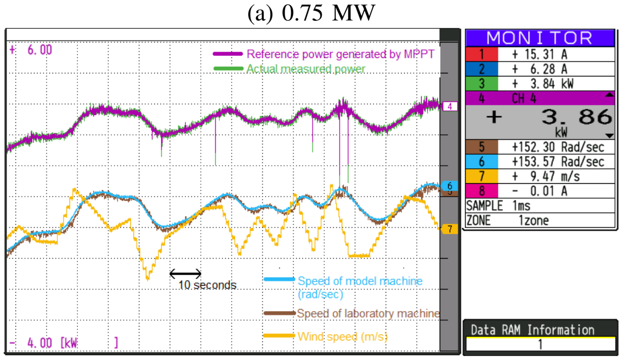


(b) 5 MW

Fig. 10: Emulation of different power rating wind turbines. Scale: Active power: 1 div. = 1kW; Rotational speed: 1 div. = 10 rad/sec; Wind speed: 1 div. = 1 m/s



(a) 0.75 MW



(b) 5 MW

Fig. 11: Emulation of wind turbines with wind profile generated from Weibull PDF. Scale: Active power: 1 div. = 1kW ; Rotational speed: 1 div. = 10 rad/sec ; Wind speed: 1 div. = 1 m/s

method on Open source software Qblade community edition is used to do the detailed aerodynamic modeling to obtain the $C_p - \lambda$ curve for different pitch angles. Hardware results demonstrate that the emulator can track the desired operating points and capture the key power–speed characteristics of the target turbines, thereby providing a realistic platform for studying grid-connected wind turbine operation and control.

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