The Design of Control System and Power Conditioning System for a 25-kW Active-control Based Wind Turbine System

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Abstract—This paper focuses on the design and technical specifications of 25-kW PMSG wind turbine system, INER-C25A, which has been undergoing field-testing since March, 2009. Three major parts of INER-C25A including the infrastructure of control system, wind turbine control strategy, and the power conditioning system will be illustrated in this paper. With the LabVIEW (Laboratory Virtual Instrument Engineering Workbench) graphical interface software tool, the embedded control system, the CompactRIO system with NI I/O modules, links sensors and drivers of sub-systems (Pitch, Yaw, and Brake) to obtain instant data and precisely control these sub-systems. By analyzing all sensor signals such as wind direction/speed, rotor speed, and temperature, the control system drives the wind turbine to trace the wind direction and to regulate the optimal pitching angle for MPPT (Maximize Power Point Tracking). The electric power generated from a PM generator is delivered to the utility grid through a 36 kW grid-tied inverter with an output voltage of 220 V/380 V (60 Hz, 3φ). The development of the control system is not only beneficial for the next generation of a new 150-kW wind turbine system, but also for establishing the design capability for the control system of large wind turbine system in Taiwan.

Keywords—Active-control; Wind Turbine System; Embedded Control System; Grid-tied Inverter.

I. INTRODUCTION

Based on system integration capability in nuclear technology, the Institute of Nuclear Energy Research (INER) has turned his research direction from nuclear area into renewable energy area since 2005. On March 2009, a 25-kW PMSG wind turbine system (INER-C25A) was set up successfully at the energy park of INER (as shown in Fig. 1) and has been undergoing field-testing. This paper focuses on the design and technical specification of INER-C25A including the infrastructure of control system, the wind turbine control strategy, and the power conditioning system. With the LabVIEW (Laboratory Virtual Instrument Engineering Workbench) graphical interface software tool, the embedded control system, the CompactRIO system with NI I/O modules, links sensors and drivers of sub-systems (Pitch, Yaw, and Brake) to obtain instant data and precisely control these sub-systems. By analyzing all sensor signals such as wind direction, wind speed, rotor speed, and temperature, the control system drives the wind turbine to trace the wind direction and to regulate the optimal pitching angle for MPPT (Maximize Power Point Tracking). The electric power generated from a PM generator is delivered to the utility grid through a 36 kW grid-tied inverter with an output voltage of 220 V/380 V (60 Hz, 3φ). The development of the control system is not only beneficial for the next generation of a new 150-kW wind turbine system, but also for establishing the design capability for the control system of large wind turbine system in Taiwan.

Figure 1. A 25-kW PMSG wind turbine system (INER-C25A) at the energy park of INER.
of system operation. Normally, the system is placed at normal procedure (manual mode), these procedures serve as the basis for normal procedures (automatic mode) and exceptional procedures (Fig. 3) are specified for the wind turbine control—mechanical subsystems including blade pitch, yaw and brake, to precisely respond to the operation conditions. Two procedures (Fig. 3) are specified for the wind turbine control—Normal procedure (automatic mode) and Exceptional procedure (manual mode), these procedures serve as the basis of system operation. Normally, the system is placed at automatic mode. In some certain circumstances, such as typhoon, maintenance, and emergency, the control system can be switched to manual mode to make wind turbine operate at the exceptional procedure for secure operations or maintenances. The control and monitoring architecture uses the CompactRIO hardware [1] and the LabVIEW graphical software as the control interface (Fig. 4), and enables INER-C25A to receive all sensor signals including wind direction, wind speed, rotor speed, and temperature, and to appropriately control the subsystems to response to highly changeable wind conditions for obtaining the maximum wind energy [2]. Fig. 5 shows the primary parts of the control system.

III. POWER CONDITIONING SYSTEM

In this section, we introduce the 25-kW PM generator and the 36-kW three-phase grid-tied power conditioning system of INER-C25A.

For the PM generator (Fig. 6), the specification is as followings: 1) outer rotor structure, 2) 42 poles and 45 slots, 3) rated speed: 300 rpm, 4) line-to-line output voltage: 380 Vrms, 5) 350 kg. The efficiency of this PM generator is 93.4% at rated speed of 300 rpm. Fig. 7 shows the efficiency curves under different load conditions. Most of the efficiency is more than 91% when the speed is above half of the rated speed.

A survey of recent literatures [3][4] shows many three-phase grid-tied back-to-back converters with MPPT algorithm were proposed. In addition, low voltage ride through (LVRT) technology [5] even for zero voltage ride through (ZVRT) technology are also actively under development. In the power
conditioning system of INER-C25A system, for cost down reason, we choose three tiers for power conversion (Fig. 8). The first tier is only a three-phase rectifier for ac/dc conversion. The second tier is a booster for regulating dc bus at 600V. The last tier is a three-phase grid-tied dc/ac inverter. The closed-loop control methodology of the compensator we chose is voltage feed-forward and current-loop control [6]. The control block diagram is as shown in Fig. 9, where, from (1) to (4), $G_c(s)$ is the compensator, $F_m(s)$ is the gain between the value of DSP duty-control register to the duty of PWM, $G_{id}(s)$ is the plant transfer function, and $H_i(s)$ is the gain of sensor circuits.

$$G_c(s) = K_p + \frac{K_i}{s} \quad (1)$$

$$F_m = \frac{1}{V_{ratio_{capr_to_d}}} \quad (2)$$

$$G_{id}(s) = \frac{V_{dc}}{R + sL_i} \quad (3)$$

$$H_i(s) = G_{CT\_ratio} \times G_{DSP\_gain} \quad (4)$$

The MPPT control curve (power v.s. rotor speed) strongly depends on wind speeds and the aerodynamics of wind blades [8]. Fig. 11 depicts the MPPT control curve which is obtained from CFD calculation results. Therefore, for appropriately matching the characteristic between rotor speed and power converter, we use a I-V curve (current v.s. voltage, as shown in Fig. 12) lookup table for MPPT control strategy, where voltage is proportional to the generator rotor speed and current is proportional to the output power that we plan to extract by the power converter, respectively.

IV. GROUND TEST AND FIELD TEST RESULTS

To verify the performance and important design parameters of the wind turbine before real field testing, a 200-kW ground
test platform (or Dyno) is built up at a machine shop of INER. Once we have finished the assembling of wind turbine system excluding blades, we directly connect the rotor shaft of the wind turbine system with this Dyno (Fig. 13) and then, perform system functionalities and power performance tests. Different from traditional ground test platforms which can only provide fixed rotor speed or fixed torque testing, our Dyno can provide specific wind blade output behavior (rpm v.s. N-m) [9][10] with respect to different wind speeds calculated from CFD. The output torque of the Dyno is set to be dependent on rotor speed at any presumed wind speed. It means the test platform can simulate variable wind speed conditions or even a gust. Moreover, if we put different parameters calculated from CFD according to different blade shapes, we can simulate the blade output belonging to that blade shape. That means we can test different kinds of blade performances in this ground test platform. It is very helpful for the design and test of the MPPT algorithm of power conditioning system under different wind speed conditions. The control system of the test platform is implemented by MATLAB/Simulink with a µ-box hardware which can be easy for modeling and integrating dynamic behaviors of blade and system. Fig. 14 illustrates the user interface of the control system at fixed wind speed mode and gust mode, respectively. In Fig. 14(b), we can see the power conditioning system makes the wind turbine operate at red points under variable wind speeds, which means it operates at maximum power point and fits the MPPT control curve well.

Fig. 15 shows the measured output voltage and current curve under 9 kW, 18 kW, 27 kW, 36 kW load conditions by connecting wind turbine system with the ground test platform. The THD decreases with the increase of load. The THD and the efficiency are 3.84% and 92.5% at rated power of 25 kW, respectively. The experimental results of output power, power factor, and system efficiency under different rotor speeds are illustrated in Table 1.

Since March 2009, INER-C25A has practically been tested at the energy park of INER. Fig. 16 depicts the measured data of wind speed, generator power and rotor speed in Phase I of field tests. It should be noted that the peak output power achieves 25 kW at 58 rpm rotor speed and around 10 m/s averaged wind speed, which broadly meets what we designed and expected. In Phase II of field tests, we will raise up the rotor speed limitation to 65 rpm to perform larger power testing and verify the functionality of the protection mechanism.

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**TABLE I. EXPERIMENTAL RESULTS**

<table>
<thead>
<tr>
<th>Rotor Speed (rpm)</th>
<th>V_{L\text{-}ph} (V)</th>
<th>P_{i} (kW)</th>
<th>P_{o} (kW)</th>
<th>PF</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>80.3</td>
<td>1.23</td>
<td>0.54</td>
<td>0.439</td>
<td>43.90</td>
</tr>
<tr>
<td>145</td>
<td>105</td>
<td>2.56</td>
<td>1.83</td>
<td>0.715</td>
<td>71.48</td>
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<tr>
<td>182</td>
<td>131</td>
<td>4.64</td>
<td>3.79</td>
<td>0.817</td>
<td>81.68</td>
</tr>
<tr>
<td>218</td>
<td>155</td>
<td>7.76</td>
<td>6.78</td>
<td>0.874</td>
<td>87.37</td>
</tr>
<tr>
<td>255</td>
<td>180</td>
<td>12.1</td>
<td>10.7</td>
<td>0.884</td>
<td>88.43</td>
</tr>
<tr>
<td>291</td>
<td>203</td>
<td>17</td>
<td>15.1</td>
<td>0.888</td>
<td>88.82</td>
</tr>
<tr>
<td>326</td>
<td>226</td>
<td>22</td>
<td>19.8</td>
<td>0.912</td>
<td>90.00</td>
</tr>
<tr>
<td>361</td>
<td>247</td>
<td>27.1</td>
<td>24.8</td>
<td>0.951</td>
<td>92.50</td>
</tr>
</tbody>
</table>

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Figure 13. The 200-kW ground test platform.

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Figure 14. The user interface of the control system in (a) fixed wind speed mode and (b) gust mode.
Although, it still needs efforts to improve the system performance and the THD reduction by adjusting the parameters of the MPPT control curve, however, we believe the success of INER-C25A brings us great encouragement and experiences for designing and testing a wind turbine system in the future.

V. CONCLUSIONS AND FUTURE WORKS

The control system and control strategy are the core technologies for a wind turbine system. Different control strategies should be applied on different wind turbine systems to maximize wind energy extraction and to optimize the protection of mechanical structures during operation. The success of INER-C25A represents not only a well established system design capability of medium size wind turbine in Taiwan, but also the possibility for designing a large wind turbine system in the future. In conclusion, the collection and analysis of the operational data will be the focus in the near future and therefore, how to design the effective way to feedback these operational data into early design phase will be the important issue in upcoming works.

REFERENCES