

Performance Comparison of Sensor and Sensorless Active Damping LCL Filter for Grid Connected of Wind Turbine

Surasak Nuilers and Bunlung Neammanee*

Abstract— This paper presents and compares the performance of sensor and sensorless active damp LCL filters for a grid-connected wind turbine. The first method measures the filter capacitor voltage that is used as a feedback to a high pass filter for a current regulator loop to stabilize and improve the system performances. This method needs additional three voltage sensors. The second method uses the same control algorithm but needs the estimation of filter capacitor voltage instead of measurement. The results from a case study with 5 kW and 10 kW loads show that although the total harmonic distortion at the grid side of both methods complies with the IEEE 519-1992, IEC 61000-3-2/IEC 61000-3-4 standards, the active damp LCL filter with a filter capacitor voltage sensor gives better performance (lower THD_i and settling time to step input) than the sensorless one.

Keywords- Active damp, LCL filter, sensorless active damp, grid connected for wind turbine.

1. INTRODUCTION

Wind energy has long been recognized as one of the alternative options for electricity production and is gaining increasing importance throughout the world because it is pollution-free, affordable and sustainable. In general, power from a wind turbine highly depends on wind speed (i.e., power increases rapidly with wind speed). There are many types of wind generators such as DC generator, synchronous generator and induction generator for electricity production and coupling to grid via grid connected converter. The total harmonic distortion of the grid current needs to comply with IEEE 519-1992, IEC 61000-3-2/IEC 61000-3-4 standard (the THD of grid current below 5%). The grid connected converter is interesting as it can be used as a front end of renewable resources and has many advantages such as 1) DC-bus voltage regulation, 2) near sinusoidal grid current, 3) controllable active and reactive power, and 4) bidirectional power flow.

Normally, the grid current of a grid connected converter contains high frequency components caused by the PWM switching frequency. The harmonic frequency is generally between 2 kHz to 15 kHz and causes high order harmonic components that can disturb other EMI sensitive loads/equipment on the grid [1], [2]. A high value for the ac inductance can solve this problem, but this makes it costly and bulky. On the contrary, to adopt an LCL filter configuration allows to use reduced values of the inductances (preserving dynamic) and to reduce the switching frequency pollution emitted in the grid [3]. An LCL filter is more effective and reduces harmonic distortion at lower switch frequency than an L filter. However, an LCL filter will bring stability problem at

resonance frequency. One solution is to use a damping resistor which is in series or parallel with the filter capacitor and this is called "passive damping." This method will increase the losses and decrease the efficiency of the system. Other solution is to modify control algorithm to stabilize the system which is called "active damping (AD)".

A control of the active damp LCL filter for the grid connected converter has two control loops. The inner loop is the current loop and the outer loop is the voltage loop. The feedback signal of these two loops is the converter currents and the DC-bus voltage respectively. In addition, the active damp LCL filter requires the voltages across the filter capacitors and filter the high frequency component of this signal. This signal is used to compensate the output of current control loop in order to eliminate the high frequency components of the converter currents. The active damp LCL filter requires three additional voltage sensors (at the filter capacitors) and therefore it is costly and difficult for installation. The sensorless active damp (without voltage sensors at the filter capacitors) is a solution to these problems by estimating the filter capacitor voltages. Although this decreases the control performances of the filter, it still complies with the standard.

This paper presents mathematical models, algorithm of sensorless active damp and implementation of a 10 kW active damp LCL filter and a sensorless active damp LCL filter. The mathematical models of a three phase grid connected converter with LCL filter are explained in Section 2. The current control block diagram is developed using vector and decoupling controls in d-, qaxis synchronous reference frame to achieve the independent control between active and reactive power in Section 3. Before implementation, the control block diagrams are simulated with MATLAB SIMULINK to verify the control performances and the behavior of the proposed system. The control algorithms are implemented on a DSP board and experimentally performed to verify their dynamic and steady responses are provided in Section 4. Section 5 concludes the paper.

Surasak Nuilers and Bunlung Neammanee are with Department of Electrical Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Thailand. Phone: +66-81-841-9399; Fax: +66-2-585-7350; E-mail: <u>snl kmutnb@hotmail.com</u> and bln@kmutnb.ac.th.



Fig. 1. Power diagram three phase PWM boost rectifier with LCL filter.

2. MATHTEMATICAL MODEL OF SYSTEM

Figure 1 is a three phase PWM boost rectifier with an LCL filter connected to the grid on the left hand side. The LC filter is in the shaded box on the left hand side and a conventional PWM three phase rectifier in the box on the right hand side. The mathematical model of a conventional system of capacitor voltages, e_a , e_b , and e_c , converter current, I_{conv} , capacitor current, T_{cap} , converter power, \mathcal{P}_{conv} , and DC-bus voltage, V_{dc} , in a, b, c-axis can be transformed into two phase d, \mathcal{P}_{-} -axis as shown in (1)-(6) [4]. The mathematical model of the LCL filter is analyzed by the LC filter cascaded with the conventional PWM three phase boost rectifier. The equation of grid voltages, V_{sa} , V_{sb} and V_{sc} , and inductor currents, i_{L2a} , i_{L2b} , i_{L2c} in d, q-axis are shown in (7)-(10).

From (1)-(6), a block diagram of the conventional PWM three phase rectifier in the two phase synchronous reference frame (d, q-axis) with single stage inductance [4] can be constructed. Equations (7)-(10) are used to construct the block diagram of the LC filter cascaded to the single stage inductance [5]. The control criteria of the PWM three phase rectifiers are to regulate the DC-bus voltage and to independently control of active power through d-axis current and reactive power through q-axis current respectively.

$$\mathbf{e}_{\mathrm{d}} \quad \mathbf{s}_{\mathrm{L}_{1}} \mathbf{i}_{\mathrm{L}_{1}\mathrm{d}} \qquad \mathbf{L}_{\mathrm{1}} \mathbf{i}_{\mathrm{L}_{1}\mathrm{q}} \qquad \mathbf{v}_{\mathrm{dn}} \tag{1}$$

$$\mathbf{e}_{\mathbf{q}} \quad \mathbf{s}_{\mathbf{L}_{1}}\mathbf{i}_{\mathbf{L}_{1}\mathbf{q}} \qquad \mathbf{L}_{\mathbf{1}}\mathbf{i}_{\mathbf{L}_{1}\mathbf{d}} \qquad \mathbf{v}_{\mathbf{q}\mathbf{n}} \tag{2}$$

$$I_{conv} = \frac{P_{conv}}{V_{dc}} = \frac{3}{2} \frac{e_d i_{L1d}}{V_{dc}} \frac{e_q i_{L1q}}{V_{dc}}$$
(3)

 $I_{cap} \mathcal{F} \mathcal{T}_{conv} T \mathcal{T}_{load} \tag{4}$

$$P_{conv} = \frac{3}{2} e_d i_{L1d} = e_q i_{L1q}$$
(5)

$$V_{dc} = \frac{1}{C} I_{cap} dt$$
 (6)

$$v_{sd} \quad sL_2i_{L2d} \quad L_2i_{L2q} \quad e_d \tag{7}$$

$$v_{sq} \quad sL_2i_{L2q} \quad L_2i_{L2d} \quad e_q \tag{8}$$

$$i_{L2d} e_d C_f s i_{L1d} C_f e_q$$
 (9)

$$i_{L2q} e_q C_f s i_{L1q} s C_f e_d$$
 (10)

3. CURRENT CONROL OF LCL WITH ACTIVE DAMP

3.1 Current Control Loop

The three phase LCL filter in Fig.1 can be written into per phase equivalent circuit model as shown in Fig.2. From this figure, a mathematical equation of the grid side current, i_{L2a} , the converter side current, T_{L1a} and filter capacitor voltage, Te_a can be derived as shown in (11)-(13).



Fig. 2. Per phase equivalent of LCL filter phase a.

$$i_{L2a} = \frac{V_{sa} - e_a}{L_2 s}$$
(11)

$$i_{L1a} = \frac{e_a V_{an}}{L_1 s}$$
(12)

$$e_{a}$$
 (i_{L2a} i_{L1a}) 1/C_fs (13)

Figure 3 shows a block diagram of single phase

current control loop. Equations (11)-(13) are used to construct the per phase LCL filter block diagram in the dash box. The voltage and current sensors and PWM are substituted by first order delays. An additional voltage sensor is required to measure the filter capacitor voltage, earline sent to a high passive filter, HPF, in the next box. These two boxes are used in the active damping process [5].



Fig.3. Current control loop with active damping.



Fig. 4. Bode plot of the LCL filter with undamp and active damp a) magnitude and b) phase.

With the MATLAB SIMULINK software package, the frequency response of the current loop of Fig. 3 can be shown in Fig. 4. The bode plot of magnitude and phase of LCL filter with undamp (blue dash line) and active damping (red line) are shown in Fig. 4. To have a current loop stable, resonant peak should be below 0 dB because the phase angle in vicinity of resonant frequency is larger than 180°, as shown in Fig. 4 b). In order to reduce the resonant peak, this paper is improved by a current control loop. The current control loop uses the high frequency component of voltage across the filter capacitor to compensate the reference voltage as shown in Fig. 3 (in the red blocks). The red line in Fig. 4 confirms the effectiveness of the improved current control loop.

3.2 Filter Capacitor Voltage Estimator

The per phase equivalent circuit model of the LCL filter of phase a is shown in Fig.2. By Kirchhoff's voltage law, the filter capacitor voltage, e_a is the summation of voltage across L₁ and R_{1.27} and the converter voltage, v_{an} as shown in (14). From (14), we can calculate the filter capacitor voltage instead of measurement if we know the value of L_1 , i_{L1a} and the converter voltage, V_{an} . Unfortunately, the converter voltage is not known but it can be estimated. The filter capacitor voltage estimator, \hat{e}_a , is shown in (15). The converter voltage of phase a, b and c can be estimated by (16), (17) and (18) respectively [8], where S_1 , TS_2 and TS_3 are the switching pattern of each phase a, b and c respectively [8].

$$\mathbf{e}_{\mathbf{a}} \quad \mathbf{L}_{1} \frac{\mathrm{d}\mathbf{i}_{\text{L1a}}}{\mathrm{d}\mathbf{t}} \quad \mathbf{v}_{\mathbf{an}} \tag{14}$$

$$\hat{e}_{a} = L_{1} \frac{di_{L1a}}{dt} = \hat{v}_{an}$$
(15)

$$\hat{v}_{an} = V_{dc} / 3 2S_1 S_2 S_3$$
 (16)

$$\hat{V}_{bn} = V_{dc} / 3 2S_2 S_1 S_3$$
 (17)

$$\hat{v}_{cn} = V_{dc} / 3 2S_3 S_1 S_2$$
 (18)

3.3 System Control Block Diagram

The overall control block diagram of the sensorless active damping LCL filter in Fig.5 consists of two main parts. The first part is a power unit as described in Fig. 1 (right hand side). The second part is a control unit consisting of a phase lock loop (PLL), a high filter (HPF) [6], [7], an axis transformation (three phase to d-, q-axis), three PI controllers, an axis transformation from d-, q-axis to a three phase and a space vector pulse width modulation (SVPWM) (left hand side) module.

To be operated in the rectifying mode, the three-phase voltage-source PWM rectifier obtains the reference angle, θ , from the phase locked loop with the phase input voltage, *ea* and *eb*. The power from the grid via the three phase LCL filter is used to boost the voltage to the DC-bus voltage. The DC output is connected with a filter capacitor and loads. The power unit has three current sensors (two for line side and one for DC-bus current) and six voltage sensors (two for PLL, three for capacitor voltages and one for DC-bus voltage). When the converter is operated in the inverting mode, the active power in the capacitor is injected via the converter to the grid to regulate the DC-bus voltage or vice versa [3], [8].

The digital signal processing controller controls the system with two references. One is i_{sq}^{*} for reactive power control (zero reactive power) and the other is V_{dc}^{*} for DC-bus voltage control (650V). Both references are the inputs of the PI controllers. In order to meet the EMC standards, three phase filter capacitor voltages are measured and transformed into d-, q-axis before being passed to the HPF. These signals are sent to compensate the output of the PI controller before they are changed to d-, q-axis voltage and then transformed to three phase voltage. This voltage is converted to drive signal by the SVPWM to control the converter.



Fig.5. Overall control block diagram of sensorless active damping LCL filter for grid connected converter.

4. CASE STUDY

The test system is shown in Fig. 6. The upper left corner of the figure is composed of a DC supply for inverting mode testing, a DC load and a DC-bus capacitor C $(3,300\mu F)$. This part can increase the DC voltage higher than the bus voltage to supply the active power in inverting operation. The figure on the upper right is composed of a three phase 10 kW PWM converter, three phase converter side inductors L_1 , three phase filter capacitors C, $(18\mu F)$ and three phase the grid side inductors L. The lower part is composed of signal conditioner and PWM gate drive system connected to a digital signal processors (DSP) board, an oscilloscope and a personal computer. The controller board uses a high performance 16 bits TMS320LF2407A. This system is designed to regulate the DC-bus voltage at 650 V and unity power factor with bi-directional power flow. Two kinds of filters; active damp LCL filter sensor and sensorless of filter capacitor voltage are tested. The controller is implemented in the DSP and linked with a personal computer via JTAG port. The value of parameters (e.g., $V_{dc},\, v_{sd},\, v_{sq},\, i_{L1d},\, i_{L1q})$ in the DSP will be sent through a digital to analog for display to verify the control performances. The picture of the experiment system is shown in Fig. 7. The experiments tests the three phase PWM boost rectifier with active damp LCL filter at 650 V DC-bus with the 10 kW load by changing two types of the filters and investigate the converter side current, the grid side current, the grid voltage and total

harmonic distortion of each current. The parameters of filter are shown in table 1.

Table 1. Parameters for test system.

Parameter	Value
Grid voltage, v _s	$400V_{L-L_{t}}(rms)$
Grid frequency, f_1	50 Hz
DC-bus voltage, V_{dc}	650V
Rated of power converter, P_{conv}	10 kW
Converter side inductor, $L_1 \times 3$	$4 \text{ mH} \times 3$
Grid side inductor, $T_{27} \times 3$	$0.5 \text{ mH} \times 3$
Filter capacitor, $C_{fT} \times 3$	18 μF × 3
DC-bus capacitor, C	3.3 mF
Switching frequency, f_{sw}	5 kHz

4.1 Active damp LCL filter with filter capacitor voltage sensor

To investigate steady state response of the active damp LCL filter in the rectifying mode and the inverting mode, the following experiments are performed:

1) Run the system in Fig.6, close switch S1 to connected the 10 kW load to the DC-bus until the system reach to the steady state condition, and measure the phase current at the converter, i_{L1a} , and the grid side , i_{L2a} , of phase a as shown in Fig. 8. From the figure, the converter side current has a high frequency component

and higher THD_i (3.3%) than that of the grid side current (THD_i = 2.9%). The grid side current, i_{L2a} , and the grid voltage, V_{sa} , of phase a are shown in Fig.10 a) with unity power factor.



Fig.6. Test system.



Fig.7. Experimentation system.



Fig. 8. Converter side and grid side current in phase *a* with capacitor voltage sensor.



Fig. 9. DC-bus voltage and grid current when step response from 5 to 10kW of the active damp LCL filter.



Fig. 10. Grid current and voltage of phase *a* with active damp LCL filter a) rectifing mode b) inverting mode.



Fig.11. Measurement, e_a , and estimate, \hat{e}_a , the filter capacitor voltage.



Fig.12. Converter side and grid side current in phase *a* with sensorless capacitor voltage.



Fig.13. Grid current and voltage of phase *a* with sensroless active damp LCL filter a) rectifing mode b) inverting mode.



Fig. 14. DC-bus voltage and grid current when step respone from 5 to 10kW of the sensorless active damp LCL filter.

2) Run the system in Fig.6, take load 5 kW at the DCbus and wait until the system reach to steady state, step up to 10 kW at time t_1 , and measure the grid side , i_{L2a} , of phase a and the DC-bus voltage, V_{dc} as shown in Fig.9. It is clearly seen that the LCL filter with active damp has to reach the steady state within 100 milliseconds.

Run the system in Fig.6, deliver 10 kW from DC supply for inverting test mode to the DC-bus until the system reach to the steady state condition, and measure the grid side , i_{L2a} , and the grid voltage, v_{sa} of phase **a** as shown in Fig. 10 b). From Fig.10, the grid connected converter with active damp LCL filter can absorb or deliver the active power to the grid.

4.2 Active damp LCL filter with sensorless filter capacitor voltage

This experiment uses the voltage estimator for filter capacitor instead of measurement for active damp LCL filter and has the same testing procedures as in the previous section.

Figure 11 shows the measurement filter capacitor voltage of phase $\mathbf{a}, \mathbf{E}_{\mathbf{a}}$, and it estimate, $\hat{\mathbf{e}}_{\mathbf{a}}$.

Figure 12 shows the converter side current, i_{L1a} , and the grid side current, i_{L2a} in phase a. In the figure, the converter side current has a high frequency component and higher THD_i (5.8%) than that of the grid side current

 $(THD_i = 4.9\%).$

Figure 13 shows the grid side current, i_{L2a} , and the grid, v_{sa} , voltage of phase a for rectifying mode (Fig.13 a) and inverting mode (Fig.13 b)). From the figure, the grid connected converter can absorb and deliver the active power to the grid.

Figure 14 shows the dynamic response of sensorless active damp LCL filter is tested by running the converter with a load of 5 kW at the DC-bus. The load is suddenly stepped to 10 kW at time t_1 . It is clearly seen that the LCL filter with active damp have to reach the steady state within 110 milliseconds.

 senserless capacitor filter voltage

 Active
 THD_i phase a
 Setting time

Table 2. The comparison LCL filter with sensor and

Active	Active THD _i ph		Setting
damp with	Converter side	Grid side	(ms)
sensor	3.3%	2.9%	100
sensorless	5.8%	4.9%	110

Table 2 compares the total harmonic distortion of current, THD_i , of phase a and the setting time of the active damp LCL filter with sensor and senserless capacitor filter voltage. Although the active damp with sensor has better performance than the sensorless, both THD_i at the grid side less than 5 % and setting time near the same.

5. CONCLUSION

This paper implements and compares the performances of sensor and sensorless active damp LCL filters. The filters and converter controller software are integrated and developed in a TMS320LF2407A board. The converter regulates the DC-bus voltage at 650V and unity power factor by controlling the *d*-axis and the *q*axis current respectively. Two experiments are conducted for measuring the dynamic and steady state responses. The dynamic response of the system was tested by a step DC load from 5 kW to 10 kW. The THDi, high frequency of current component in converter sides and the grid side current and power factor are measured.

The advantages of both methods are smaller size of inductors, no high frequency of the current and faster dynamic response. The experimental results can verify that the active damp LCL filter with filter capacitor voltage sensor gives a better performance (lower THD_i and setting time to the step input) than the sensorless one. However, this method introduces the cost of purchase and installation for voltage sensors and is difficult to install these sensors to the old system (L filters). The sensorless LCL filter overcomes these disadvantages by estimating of filter capacitor voltage. Although the performances of filter are lower, it can compile with the standards. Therefore, the sensorless LCL filter not only minimizes the number of sensors and

its installation cost, but also optimizes the filter performances.

ACKNOWLEDGMENT

The authors would like to thank the University-Industry Research Collaboration (U-IRC), National Science and Technology Development Agency, Ministry of Science and technology for finance support and Novem Engineering Co., ltd. for equipment and valuable suggestion.

NOMENCLATURE

L_1, T_2	=	inductance of converter side and the grid side
R ₁ , R ₂	=	internal resistance of each inductors
C _f	=	filter capacitor
С	=	DC-bus filter capacitor
$i_{L1a}, T_{L1b}, T_{L1c}$	=	converter current in phase a, B, E
i_Ca, T_Cb, T_Cc	=	filter capacitor current in phase a, b, c
$\mathbf{V}_{an}, \mathcal{U}_{bn}, \mathcal{U}_{cn} T$	=	converter voltage in phase a, B, E
I _{load}	=	load current
e _d , e _q	=	filter capacitor voltage in d, 7 axis
i _{L1d} , i _{L1q}	=	converter current in d, 72-axis
V_{sd}, V_{sq}	=	grid voltage in d, Z -axis
i_{L2d}, i_{L2q}	=	grid current in d, 2 p-axis
$\hat{\mathbf{v}}_{an}, \hat{\mathbf{v}}_{bn}, \hat{\mathbf{v}}_{cn}$ T	' =	estimate filter converter voltage in phase $a, \mathcal{B}, \mathcal{T}$
$\hat{\mathbf{e}}_{a}, \hat{\mathbf{e}}_{b}, \hat{\mathbf{e}}_{c} T$	=	estimate filter capacitor voltage in phase $a, \mathcal{B}, \mathcal{E}$
ê _d ,ê _q	=	estimate filter capacitor voltage in d, q-axis

REFERENCES

- Liserre, M., Blaabjerg, F., and Hansen, S. 2001. Design and control of an LCL-filter based active rectifier. In *Proceedings of IEEE Transactions on Industry Applications* 41(5): 299-307
- [2] Teodorescu, R., Blaabjerg, F., Liserre, M., and Dell'Aquila, A. 2003. A stable three-phase LCLfilter based active rectifier without damping. In *Proceedings of IEEE Transactions on Industry Applications* 3: 1552-1557.
- [3] Liu C.-Y. and Huang, S. 2008. The Development of Active Controllable Energy Feedback Device Based on d-q Model. In *Proceedings of International Conference on*: 1711-1715
- [4] Sudmee, W. and Neammanee, B. 2007. Performance Comparison of DC Link Voltage Controllers in Vector Controlled Boost Type PWM Converter for Wind Turbine. In *Proceedings of Power Electronics* and Drive Systems, 7th International Conf: 930-936.

- [5] Blasko, V. and Kaura, V. 1997. A novel control to actively damp resonance in input LC filter of a three-phase voltage source converter. In *Proceedings of International Conference On* 33(1): 542-550.
- [6] Malinowski, M., Szczygiel, W., Kazmierkowski, M. P., and Bernet, S. 2005. Simple Sensorless Active Damping Solution for Three-Phase PWM Rectifier with LCL Filter. In *Proceedings of Industrial Electronic Society, Annual Conference of IEEE*: 1-5.
- [7] Malinowski, M., Szczygiel, W., Kazmierkowski, M.P. and Bernet, S. 2005. Sensorless Operation of Active Damping Methods for Three-Phase PWM Converters. In *Proceedings of the IEEE International Symposium on Industrial Electronics*. Reiburg, Poland, 14 November.
- [8] Yu, Z. 1999. Space-Vector PWM With TMS320C24x/F24x Using Hardware and Software Determined Switching Patterns. Literature Number: SPRA524. USA : Texas Instruments Incorporated.

S. Nuilers and B. Neammanee / GMSARN International Journal 5 (2011) 71 - 78