Compensation of Unbalanced PCC Voltage in Off-shore Wind Farms of PMSG Type Turbine

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ABSTRACT

This paper proposes a control algorithm for permanent magnet synchronous generator with a back-to-back three-level neutral-point clamped voltage source converter in a medium-voltage offshore wind power system under unbalanced grid conditions. The proposed control algorithm particularly compensates for the unbalanced grid voltage at the point of common coupling in a collector bus of offshore wind power system. This control algorithm has been formulated based on the symmetrical components in positive and negative rotating synchronous reference frames under generalized unbalanced operating conditions. Instantaneous active and reactive power are described in terms of symmetrical components of measured grid input voltages and currents. Negative sequential component of ac input current is injected to the point of common coupling in the proposed control strategy. The amplitude of negative sequential component is calculated to minimize the negative sequential component of grid voltage under the limitation of current capability in a voltage source converter. The proposed control algorithm makes it possible to provide a balanced voltage at the point of common coupling resulting in the generated power of high quality from offshore wind power system under unbalanced network conditions.

1. Introduction

Wind power system is one of the fastest growing renewable energy systems. In large scaled MW-range wind turbines, PMSG (Permanent Magnet Synchronous Generator) type wind turbines involving a full-scaled PCS (Power Conditioning System) becomes a dominant choice due to its superb performance in active and reactive power generation.

Recently, grid codes about LVRT and operation under grid unbalances become more strict. In general, unbalanced current is caused by unbalanced grid conditions, and it leads to unbalanced voltage at PCC (Point of Common Coupling). These unbalanced voltage conditions generate ripple and distortion of dc-link and grid current [1]. Most of studies regarding unbalance grid input focused on stabilizing the operation of wind turbine PCS itself, i.e. reducing the harmonics in ac input current and dc link voltage, or compensating unbalanced grid current [1 and 2]. There have been several studies trying to solve PCC unbalanced problem. Some papers proposed a compensating solution employing an additional active power filter at PCC [3]. Other papers proposed compensation for unbalanced voltage at PCC using STATCOM[4]. There has been a little work dealing with PCC unbalance problem solely by PCS itself without employing additional active filter or STATCOM.

This paper proposes a control algorithm to actively compensate for the unbalanced grid voltage at PCC. Negative sequence current is injected to the grid to cancel the negative sequential component of grid voltage at PCC. The amplitude of injected negative sequence current is computed under the limit of maximum input current of PCS. Proposed control algorithm performs under the current capability of PCS. As a result, proposed control algorithm improves the quality of output power from wind farm within the current capability limit of PCS. Detailed calculation result as well as simulation result of 2.7MW wind turbine of PMSG type is provided to validate the proposed control algorithm in this paper.

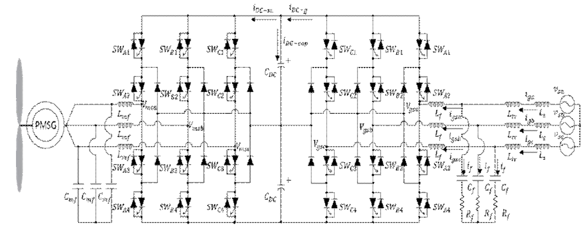

Fig 1 PMSG wind turbine with a back-to-back 3-Level NPC VSC

2. Modeling of PMSG under Grid Unbalance

Under unbalanced grid voltage, PMSG can be effectively modeled by using both positive and negative sequence components of voltages and currents. The positive and negative sequence components in a synchronous rotating frame are expressed as followings.

$$V^p_{gsd}-\omega L_f I^p_{gsq}+L_f\frac{d}{dt}I^p_{gsd}=V^p_{sd}+\omega(L_{tr}+L_s)I^p_{gq}-(L_{tr}+L_s)\frac{d}{dt}I^p_{gd} \quad (1)$$

$$V^p_{gsq}+\omega L_f I^p_{gsd}+L_f\frac{d}{dt}I^p_{gsq}=V^p_{sq}-\omega(L_{tr}+L_s)I^p_{gd}-(L_{tr}+L_s)\frac{d}{dt}I^p_{gq} \quad (2)$$

$$V^n_{gsd}+\omega L_f I^n_{gsq}+L_f\frac{d}{dt}I^n_{gsd}=V^n_{sd}-\omega(L_{tr}+L_s)I^n_{gq}-(L_{tr}+L_s)\frac{d}{dt}I^n_{gd} \quad (3)$$

$$V^n_{gsq}-\omega L_f I^n_{gsd}+L_f\frac{d}{dt}I^n_{gsq}=V^n_{sq}+\omega(L_{tr}+L_s)I^n_{gd}-(L_{tr}+L_s)\frac{d}{dt}I^n_{gq} \quad (4)$$

Based on the model given in (1)-(4), the equivalent circuit of grid input side of PMSG corresponding to positive and negative sequential components can be generated.

3. NCI Control Algorithm

This paper proposes *Negative sequence Current Injection* (NCI) algorithm to actively compensate for the unbalance of PCC voltage by controlling negative sequence current.

First and second control strategies are to keep PCC voltage balanced. In sequential equivalent circuit of target system, the negative sequential components of ac input current (I^n_{gd} and I^n_{gq}) are related with the negative sequential components of PCC voltage (V^n_{pccd} and V^n_{pccq}). If V^n_{pccd} and V^n_{pccq} are to be zero, then I^n_{gd} and I^n_{gq} are simplified as in (5) and (6).

$$I^n_{gd}=-\frac{V^n_{sq}}{\omega L_s} \quad (5) \qquad I^n_{gq}=\frac{V^n_{sd}}{\omega L_s} \quad (6)$$

The third and fourth control strategies are to meet the demand of active and reactive power generation. The average values of instantaneous input active and reactive power can be formulated in terms of sequential components of ac input voltage and current as followings.

$$-\frac{2}{3}P^{in}_{so}=V^p_{sd}I^p_{gd}+V^p_{sq}I^p_{gq}+V^n_{sd}I^n_{gd}+V^n_{sq}I^n_{gq} \quad (7)$$

$$-\frac{2}{3}Q^{in}_{so}=V^p_{sq}I^p_{gd}-V^p_{sd}I^p_{gq}-V^n_{sd}I^n_{gd}+V^n_{sq}I^n_{gq} \quad (8)$$

Finally I^p_{gd} and I^p_{gq} can be obtained.

$$I_{gd}^{p} = \frac{1}{(V_{sd}^{p})^2 + (V_{sq}^{p})^2}\{\frac{2}{3}P_{so}^{in}(-V_{sd}^{p} - V_{sq}^{p}k_{pf}) + \frac{(-V_{dq}^{p} + V_{sq}^{p})V_{sd}^{n}(-V_{sq}^{n}) - (V_{dq}^{p} + V_{sq}^{p})V_{sd}^{n}V_{sq}^{n}}{\omega L_s}\} \quad (9)$$

$$I_{gq}^{p} = \frac{1}{(V_{sd}^{p})^2 + (V_{sq}^{p})^2}\{\frac{2}{3}P_{so}^{in}(-V_{sq}^{p} + V_{sd}^{p}k_{pf}) + \frac{(-V_{dq}^{p} - V_{sq}^{p})V_{sd}^{n}(-V_{sq}^{n}) + (V_{dq}^{p} - V_{sq}^{p})V_{sd}^{n}V_{sq}^{n}}{\omega L_s}\} \quad (10)$$

As a result, the positive and negative sequential components of ac input grid currents (I_{gd}^{p}, I_{gq}^{p}, I_{gd}^{n}, and I_{gq}^{n}) are calculated from four equations of (5), (6), (9), and (10).

4. Simulation and Experiment Result

Unbalance Factor (UF) is the ratio of magnitude of negative and positive sequential components. Simulation are performed under the condition of UF=3%. Parameters are summarized in Table I.

TABLE I
PARAMETERS OF PMSG WIND TURBINE SYSTEM

Parameter	Value	Parameter	Value
Rated power (P_{rated})	2.7 MW	Converter switching frequency (f_{sw})	1020 Hz
Rated line voltage ($V_{llrated}$)	3300 V	Grid side line inductance (L_s)	1.07 mH (0.1 pu)
Rated ac input current (I_{rated})	520 A	Transformer leakage inductance (L_{tr})	0 54 mH (0.05 pu)
Frequency (f_{in})	60 Hz	Filter inductance (L_f)	1.2 mH (0.11 pu)
DC link voltage (V_{DC})	5200 V	Filter capacitance (C_f)	0.24 mF (0.37 pu)
DC link capacitance (C_{DC})	6 mF	Filter resistance (R_f)	0 3 Ω (0.07 pu)

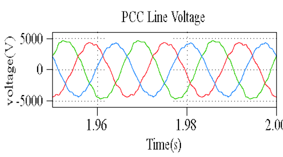

Fig 2 PCC line voltages without compensation algorithm

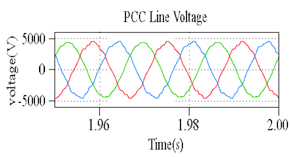

Fig 3 PCC line voltages with NCI algorithm

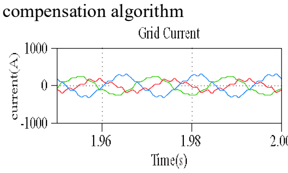

Fig 4 Grid currents without compensation algorithm

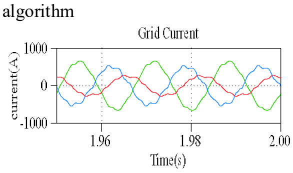

Fig 5 Grid currents with NCI algorithm

Under the grid unbalance and output power generation condition, the three-phase line voltages at PCC are illustrated in Fig. 2 and 3. Waveforms in Fig. 2 are obtained without NCI compensating algorithm being employed, i.e. the conventional single-frame current regulator of positive sequential component of ac input current only. Waveforms in Fig. 3 are obtained with NCI compensating algorithm being employed. The corresponding numerical data are summarized in Table II for the sake of readers' convenience. In Fig. 2, the unbalance factor of line voltages at PCC is close to that of grid input voltages, i.e. UF=3%. As shown in Fig. 3 and Table II, the proposed NCI control algorithm actively compensates for the unbalanced grid voltage. As a result NCI control algorithm makes the three-phase line voltages at PCC balanced having the UF of almost zero.

The compensation of grid unbalanced voltage at PCC is made possible by the injection of negative sequence current to the grid. Fig. 4 provides the waveforms of three-phase ac input currents without NCI control algorithm being considered. Fig. 5 shows the waveforms of three-phase ac input currents with NCI control algorithm considered. It is clearly noted from Fig. 5 that the three-phase ac input currents become more unbalanced as compared to those of Fig. 4 because of injected negative sequential component of input current.

TABLE II
COMPARISON OF LINE VOLTAGES AT PCC AND GRID CURRENTS

Variables	Conventional algorithm	NCI algorithm
PCC line voltage v_{ab}	4663 V_{pk}	4523 V_{pk}
PCC line voltage v_{bc}	4485 V_{pk}	4520 V_{pk}
PCC line voltage v_{ca}	4429 V_{pk}	4533 V_{pk}
UF of PCC voltage	3 1%	0%
Grid current i_a	419 A_{pk}	623 A_{pk}
Grid current i_b	380 A_{pk}	250 A_{pk}
Grid current i_c	449 A_{pk}	466 A_{pk}

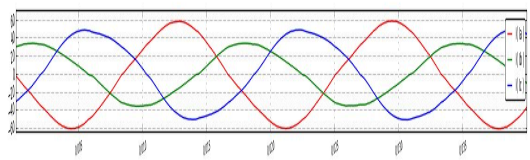

Fig 6 Experiment result of grid currents with NCI algorithm

The experiment result of proposed NCI control algorithm is described for the laboratory test setup of 36kW. Waveforms of input currents with NCI control algorithm employed are illustrated in Fig. 6. Experiment results provided in Fig. 6 exhibit the similar operational characteristic of NCI control algorithm to that of Fig. 5.

5. Conclusion

This paper proposes a negative sequence current injection algorithm to actively compensate for voltage unbalance at PCC. The algorithm is to cancel the negative sequential component of voltage by injecting the appropriate negative sequential component of input current. As the depth of unbalance becomes severe, the necessary magnitude of negative sequence current also increases over the current capability of PCS. When the output power of wind turbine gets smaller at low wind speed, the injection of negative sequence current becomes more effective under the current limit of PCS. In a wind farm consisting of multiple wind turbines connected to a collector bus, the contribution of negative sequence current generated by each wind turbine can be summed to compensate for the unbalance at PCC. The proposed control algorithm makes it possible for wind farms to generate a high quality output power under unbalance grid disturbance.

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