Control Strategy Compensating for Unbalanced Grid Voltage Through Negative Sequence Current Injection in PMSG Wind Turbines

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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 energy is one of the fastest growing renewable energy sources in the world and the number of large offshore wind farms both in operation and under construction is increasing rapidly. In large scaled MW-range wind turbines, permanent magnet synchronous generator type involving a full-scaled PCS (Power Conditioning System) becomes a dominant choice.

In general, individual wind turbine is subject to both transient and steady-state network disturbances of grid unbalance. These disturbances of grid unbalance can deteriorate the quality of output power from wind turbines and also further degrade the unbalance of network voltage at the collector bus of wind farm. There have been several studies trying to solve this unbalance problem. Some papers proposed an additional active power filter at PCC (Point of Common Coupling) [1]. Most of studies regarding unbalance grid input focused on stabilizing the operation of wind turbine PCS itself or compensating grid current [2 and 3]. Very little work has been reported to actively compensate for unbalance voltage at PCC.

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. Proposed algorithm performs under the current capability of PCS and improves the quality of output power from wind farm. Calculation as well as simulation result are provided to validate the proposed control algorithm in this paper.

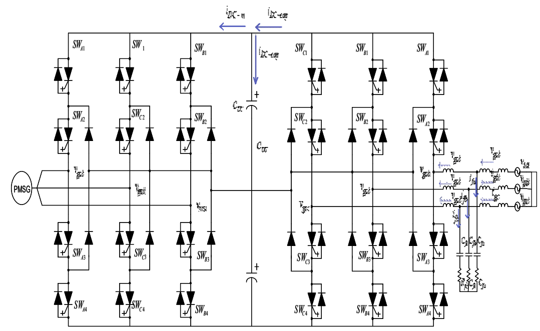

Fig 1 PMSG wind turbine with a back-to-back 3-Level NPC VSC

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 as shown in Fig. 2 and 3.

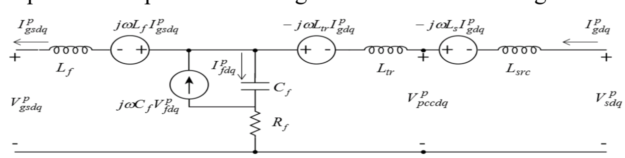

Fig 2 Equivalent circuit of positive sequence in a synchronous reference frame

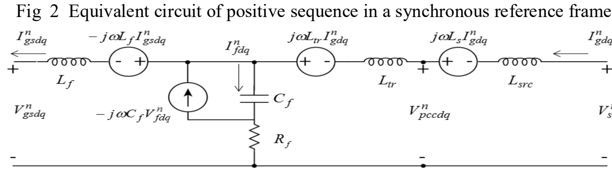

Fig 3 Equivalent circuit of negative sequence in a synchronous reference frame

3. Control Algorithm

3.1 NCI algorithm

This paper proposes *Negative sequence Current Injection* (NCI) algorithm to actively compensate for the unbalance of PCC voltage by controlling negative sequence current. Balanced PCC voltage implies that the negative sequence must be zero. Four control laws are considered to satisfy the balanced PCC voltage and active/reactive power generation conditions.

First control law: $$I^n_{gq} = \frac{V^n_{sd} - V^n_{pccd}}{\omega L_s} \quad (5)$$

Second control law: $$I^n_{gd} = -\frac{V^n_{sq} - V^n_{pccq}}{\omega L_s} \quad (6)$$

$$-\frac{2}{3}\begin{bmatrix}P^{in}_{so}\\ Q^{in}_{so}\end{bmatrix} = \begin{bmatrix}V^p_{sd} & V^p_{sq}\\ V^p_{sq} & -V^p_{sd}\end{bmatrix}\begin{bmatrix}I^p_{gd}\\ I^p_{gq}\end{bmatrix} + \frac{1}{\omega L_s}\begin{bmatrix}-V^n_{sd} & V^n_{sq}\\ V^n_{sq} & V^n_{sd}\end{bmatrix}\begin{bmatrix}V^n_{sq}\\ V^n_{sd}\end{bmatrix} \quad (7)$$

$$I^p_{gd} = \frac{1}{V^p_{sq}} I^p_{gq} + \frac{(V^n_{sd})^2+(V^n_{sq})^2}{\omega L_s} V^p_{sq} \quad (8)$$

$$I^p_{gq} = \frac{2}{3} P^{in}_{so} (k_{pf} V^p_{sd} + V^p_{sq}) \quad (9)$$

The positive and negative sequential components of ac input grid currents (I^p_{gd}, I^p_{gq}, I^n_{gd} and I^n_{gq}) are calculated from four control laws and used as reference values in dual-frame current regulator [2].

3.2 Modified NCI control algorithm

The negative sequential component values of ac input current (I^n_{gd} and I^n_{gq}) becomes relatively large under the condition of severe input unbalance. This algorithm is to limit the amplitude of ac input current below the current capability of PCS and try to minimize the unbalance of grid voltage at PCC.

4. Simulation Result

Unbalance Factor (UF) is the ratio of magnitude of negative sequence and positive sequence as shown in (10). Calculation and simulation are performed under the condition of UF=0.0714. Parameters of PMSG employed in the simulation are summarized in Table I.

$$UF = \sqrt{\frac{(V^n_{sd})^2+(V^n_{sq})^2}{(V^p_{sd})^2+(V^p_{sq})^2}} \quad (10)$$

TABLE I
PARAMETERS OF PMSG WIND TURBINE SYSTEM

Parameter	Value	Parameter	Value
Rated power (MW)	2 7	Grid side line inductance (mH)	0 54
Rated line voltage (V)	3300	Transformer inductance (mH)	1 07
Frequency (Hz)	60	Filter inductance (mH)	0 08
DC link voltage (V)	5200	Filter capacitance (mF)	0 18
DC link capacitance (mF)	6	Filter resistance (Ω)	0 614

TABLE II
COMPARISON OF LINE VOLTAGE AT PCC AND GRID CURRENT (UF=0 0714)

Variables	Single-frame control algorithm (peak)	NCI algorithm (peak)	Modified NCI algorithm (peak)
PCC line voltage v_{ab}	4715V	4441V	4551V
PCC line voltage v_{bc}	4253V	4427V	4332V
PCC line voltage v_{ca}	4292V	4436V	4403V
Grid current i_a	674A	380A	256A
Grid current i_b	710A	1527A	1193A
Grid current i_c	769A	1186A	1002A

Calculation result as well as simulation result is presented in Table II and Fig. 4-9. In Fig. 6, the waveforms of voltage at PCC with NCI algorithm applied are shown to be balanced as compared to those of Fig. 4. This compensation is made possible by the injection of negative sequence current as noted in Fig. 7. The performance of modified NCI algorithm is inferior to that of NCI algorithm as demonstrated in Fig. 8 and 9. However, the peak of current is maintained below the current capability of PCS which is necessary condition in industry.

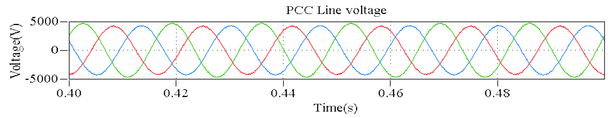

Fig 4 PCC line voltage without compensation algorithm under UF=0 0714

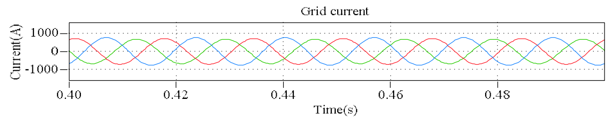

Fig 5 Grid current without compensation algorithm under UF=0 0714

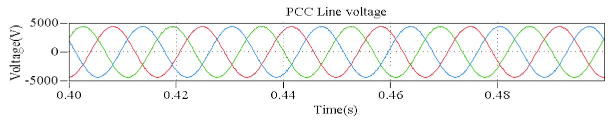

Fig 6 PCC line voltage with NCI algorithm under UF=0 0714

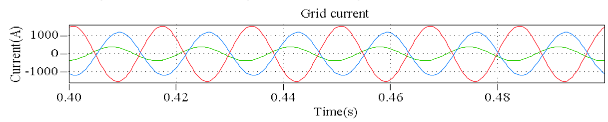

Fig 7 Grid current with NCI algorithm under UF=0 0714

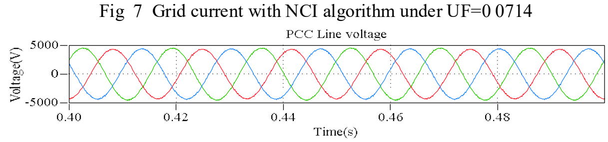

Fig 8 PCC line voltage with modified NCI algorithm under UF=0 0714

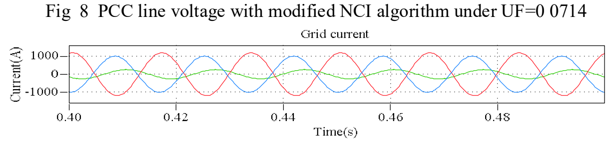

Fig 9 Grid current with modified NCI algorithm under UF=0 0714

5. Conclusion

This paper proposes a negative sequence current injection algorithm to actively compensate for the unbalance in voltage at PCC. The algorithm is to cancel the negative sequential component of voltage by injecting the appropriate negative sequential component of ac input current by PCS. As the depth of unbalance becomes severe, the necessary magnitude of negative sequence current also increases surpassing the limit of current capability of PCS. The modified NCI algorithm, also proposed in this paper, effectively minimizes the unbalance of voltage at PCC while maintaining the current amplitude below the limit. The both proposed control algorithms make it possible for wind farms to generate a high quality output power even under unbalance grid disturbance.

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