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A versatile method for computation of power pulsations in DFIG under grid imperfections

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In the context of a Doubly Fed Induction Generator (DFIG) connected to the utility grid under unbalanced voltage conditions, the controller design needs to ensure additional challenges such as restricting the Total Harmonic Distortion (THD) in grid current, minimizing the pulsations in generated power, torque, dc link voltage etc. apart from facilitating the generator power control. Thus the schemes for generating reference currents for rotor converters need to incorporate a measure of power pulsations to what is required for steady state power flow control. This paper proposes a versatile scheme for computing the power pulsations in a DFIG connected to grid under unbalance voltage conditions. The active and reactive power oscillations are computed in a simple and straight forward manner using the measured stator voltage and currents in the positive *d-q* frame without using flux estimation. The scheme is free from flux integration or differentiation, rotor position computation and independent of machine parameters. Further, the worst case error in computation is bound within 3% considering 30% voltage dip, 7% of harmonics, $\pm 10^\circ$phase jump or $\pm$10% dc offset in the grid voltage. The effectiveness of the scheme is validated through PSCAD/EMTDC simulations and experimental results for a 2.3 kW DFIG test setup.

1. Introduction

In the recent years, grid connected DFIG's are extensively used in wind power generation compared to fixed speed generators owing to the variable speed operation with reduced converter cost, comparatively low power loss and power flow control capability in sub-synchronous as well as super synchronous generating modes. Since the penetration rate of wind farms into the grid is increasing, grid codes have been developed in most of the countries for the reliable and secure operation of wind farms. The major issue that has to be tackled for the enhanced operation of DFIG is the grid voltage distortion under voltage sag and harmonics. The sags in grid voltage lead to fluctuations in stator flux and further, reflect as pulsations in electromagnetic torque and ripple in speed. This leads to mechanical stress in the rotating parts of DFIG. Moreover, there can be considerable oscillations in power as well as in dc link voltage. Whereas, harmonics in grid voltage lead to overheating of windings and power loss along with considerable oscillations at double the harmonic frequency in power and torque. Thus, under such imperfect grid conditions the controller design has to account for reducing the THD in grid current as per Indian Electricity Grid Code (IEGC) [15,16] as well as minimizing the pulsations in torque, power, dc link voltage etc. in addition to the prime task of generator power control.

Quite a number of power control schemes are reported in literature for DFIG operation under balanced and distorted grid conditions which includes Direct Power Control (DPC), decoupled power control, double vector control and simultaneous control schemes. However, double vector control schemes are intended to minimize the 100 Hz pulsations in torque, power and dc link voltage as individual control targets while the simultaneous control schemes minimizes the pulsations simultaneously. Several DPC schemes such as Stator Flux oriented (SF-DPC), Rotor Flux oriented (RF-DPC) and Predictive DPC (PDPC) schemes got remarkable attention as these schemes are free from complex current control loops. However, all the DPC schemes necessarily involve computation of pulsations in active and reactive power for precise power control especially under transient grid conditions.

Among them [1–11] includes DPC schemes for DFIG operation under balanced and distorted grid conditions where the fluctuations in power are estimated for a fixed sampling period. Further, the estimated fluctuations in power along with stator or rotor flux

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position are used for sector identification and control implementation using Space Vector Pulse Width Modulation (SVPWM) technique.

A conventional DPC scheme can lead to pulsations in electromagnetic torque [1] as the injected rotor voltages are generated from a fixed discrete switching table. SF-DPC scheme can provide improved dynamic performance even under transients whereas, RF-DPC scheme reduces the complexity in filter and converter design and PDPC scheme improves the dynamic performance of the system and is insensitive to parameter variations. However, SF-DPC and PDPC schemes introduce complexity in filter design [1]. In Ref. [2], a SF-DPC scheme is operated at varying switching frequency for reduction of oscillations in active power, torque and dc link voltage under grid voltage unbalance. The oscillating components in stator active power are estimated from the estimated active power and torque without using sequence decomposition technique whereas, the computation of oscillating components in stator reactive power and grid side active and reactive power involves sequence decomposition. Since sequence decomposition is involved, it introduces time delay in estimated oscillations. Moreover the computation of active power pulsations depends on stator resistance. Likewise, in studies based on SF-DPC scheme [3–9], DPC is achieved by injecting rotor voltages from the estimated stator flux, rotor position, and the errors associated with active and reactive powers. In Refs. [3–5], the computation of stator active and reactive power and hence power fluctuations involves machine parameters and stator flux estimation. In Ref. [6], decoupling of stator flux and deadbeat control loops is used to calculate the rotor voltage to be injected to eliminate the active and reactive power errors. The instantaneous errors in power are estimated from the discrete samples of power at different intervals which are machine parameter dependant. A scheme based on Discrete Space Vector Modulation (DSVM) is proposed for DPC of DFIG [7]. The controller accuracy is better as the number of voltage vectors generated is more.

A scheme using hysteresis controller [8] for a stand alone DFIG to control the active power delivered to the load to maintain constant dc link voltage is proposed which involves machine parameters and flux computation. The sector identification and switching is based on the instantaneous errors between the reference and estimated values of active and reactive power controlled within an arbitrary band width and angular flux position. In Ref. [9], the ripple in active and reactive power under grid unbalance are estimated using *d-q* axes negative sequence voltages and positive sequence currents to eliminate the negative sequence current components. However, power oscillations still persist. Schemes [1], [4–7] are not suitable for unbalanced situation since the rate of change of stator flux is assumed to be zero while, in Ref. [9] sequence decomposition is involved to determine the oscillating components of power causing time delay in computation.

In RF-DPC schemes sector identification is made using estimated values of instantaneous errors of active and reactive power and rotor flux position [10,11]. A hysteresis controller based sensorless scheme [10] for enhanced dynamic performance of wound rotor induction machine under balanced grid condition is reported where, the active and reactive power errors are controlled within an arbitrary band width. A double vector controlled DPC scheme to eliminate the stator active power oscillations under grid unbalance is proposed [11], where the power pulsations are computed by differentiating the rotor flux for a fixed sampling time. Thus the efficacy of the scheme depends on machine parameters. Several schemes are reported for decoupled control of active and reactive power under grid unbalance using estimated power pulsations [12,13]. The stator active power oscillations are estimated from the estimated active power and torque and reactive power oscillations are computed using the positive and negative sequence *d-q* axes components of stator voltages and currents in Ref. [12] whereas in Ref. [13], a Low Pass Filter (LPF) or High Pass Filter (HPF) is used for separating the ripple in active and reactive power which introduces phase lag or lead in the computed signal. A stator flux oriented vector control scheme [14] for simultaneous reduction of oscillations in active power, torque and dc link voltage is proposed without using dual vector control. Even though it is an effective scheme to control the power pulsations, sequence decomposition of stator voltages and currents and heuristic mathematical calculations are involved for reference current generation. However, computation of power pulsations is not involved for reference current generation.

In Refs. [17,18], DPC of DFIG using sliding mode control is proposed where the pulsations in power is determined by differentiating the active and reactive power expressed in terms of the product of α-β axes voltages and currents by avoiding the transformations in synchronous reference frame. Estimated stator flux position along with sliding mode based approach is used for sector identification and control which involves measurement of rotor currents, speed and rotor position additionally. DPC schemes using vector based Proportional Integral (PI) control in the positive *d-q* frame [19] and combined conventional vector control scheme with DPC for balanced grid conditions [20] are proposed. However the calculation of power in both schemes involves machine parameters and grid frequency. Moreover the computation of power pulsations in Ref. [19] involves computation of rotor flux. The active and reactive power errors dictate the *d-q* axes rotor reference currents [20]. The current error along with the computed rotor flux position is used for pulse generation. A sensorless DPC scheme [21] controls the active and reactive power pulsations within an arbitrary band width where, the power pulsations along with the stator flux position are used for sector identification and control.

Likewise, several model based PDPC schemes [22–24] are proposed where the computation of power pulsations involve machine parameters and computation of rotor flux along with rotor flux position for pulse generation. Moreover a few schemes [22,23], involve measurement or computation of rotor position for computing power pulsations. Thus it is evident that almost all the reported DPC schemes use either differentiation of rotor flux or differentiation of the product of voltages and currents or sequence decomposition of measured voltages and currents for computing the instantaneous pulsations in power. Even though DPC scheme provides a better dynamic performance, the differentiation of rotor flux and stator flux integration deteriorates the performance of the system. Moreover, the performance is sensitive to machine parameter variations.

In this paper, a versatile scheme is proposed for the computation of active and reactive power pulsations for reference power generation in order to enhance the performance of DFIG under grid imperfections. The attractive feature of the method is that the active and reactive power pulsations under distorted grid conditions can be computed using simple mathematical calculations making use of positive sequence components of voltage and currents in the positive sequence *d-q* frame without the need for measuring rotor currents, computing rotor position or speed. This computation scheme is simple and easy to implement. Further, the computation of power oscillations does not involve machine parameters or estimation, integration or differentiation of flux and hence better dynamic performance. PSCAD/EMTDC simulations and experimentations on 2.3 kW DFIG wind generation system validate the effectiveness of the DPC scheme with the proposed power oscillation computation method under steady-state and transient grid conditions. ALTERA Cyclone II FPGA controller is used for signal processing. Typical experimental results for the