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Fuzzy Control Strategy for Harmonics Compensation in Stand-Alone Doubly Fed Induction Generators with Nonlinear Loads

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Abstract: This letter proposes a novel method to reject 6n ± 1 harmonics in the stator voltage at the point of common coupling (PCC) for a stand-alone doubly-fed induction generator (DFIG) supplying a balanced three-phase diode rectifier. These harmonics are rejected by using the rotor current controller in the fundamental synchronous reference frame. The proposed control algorithm is based on a proportional integral controller and a bank of resonant filters. In this frame, each resonant filter in the rotor current controller has the possibility of rejecting one pair of the positive and the negative stator harmonic voltages at the PCC. Experimental results with 2.2-kW DFIG are shown in this letter.

Keywords: Doubly-Fed Induction Generator, Harmonics Rejection, Nonlinear Load, Resonant Regulator, Stand-Alone System.

I. INTRODUCTION

Doubly fed induction generator (DFIG) has been commonly used in wind energy conversion systems over the last decade. The majority of researches in the literature have developed the control and operation of the DFIG in grid-connected applications [1]. To evaluate the full potential of the DFIG, however, the developments in stand-alone case should be taken into account. It should be noted that unbalanced or nonlinear loads connected to the point of common coupling (PCC) have significant influence on the quality of the stator voltage waveform at the PCC [2]–[3]. This letter mainly focuses on the control strategy to reject harmonics in the stator voltage at the PCC of the DFIG with nonlinear loads such as balanced three-phase diode rectifiers. Under such nonlinear loads, severe odd harmonics regularly appear in the stator voltage at the PCC with 6n ± 1 (n = 1, 2, . . .) multiples of synchronous frequency ωs, shown in [4] Fig.1. This letter presents a general method based on the rotor current regulation in the rotor-side converter (RSC) to remove these harmonic voltages effectively. The proposed harmonic rejection algorithm is based on three important steps:

- Extracting voltage harmonic components of the stator voltage at the PCC and driving them to zero.
- Developing a rotor current reference generation strategy to be regulated in the RSC.
- Adopting a PI regulator and a bank of resonant filters (PI-R) in the fundamental reference frame.

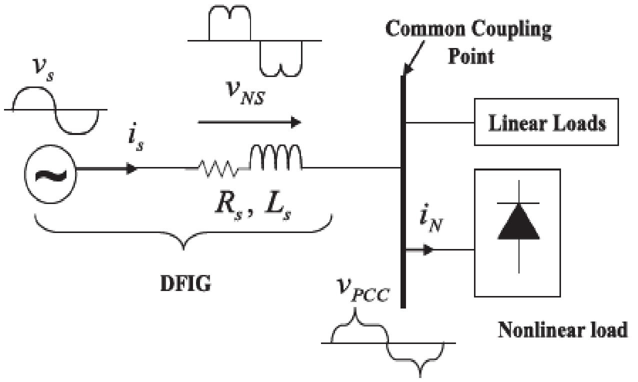

Fig.1. Connection interface between the DFIG and loads.

II. DOUBLY FED INDUCTION GENERATOR

Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed. Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generator.

A. Operating Principle of DFIG

The stator is directly connected to the AC mains, whilst the wound rotor is fed from the Power Electronics Converter via slip rings to allow DIFG to operate at a variety of speeds in response to changing wind speed. Indeed, the basic concept is to interpose a frequency converter between the variable frequency induction generator and fixed frequency grid. The DC capacitor linking stator-and rotor-side converters allows the storage of power from induction generator for further generation. To achieve full control of grid current, the DC-link voltage must be boosted to a level higher than the amplitude of grid line-to-line voltage The slip power can flow in both directions, i.e. to the rotor from the supply and from supply to the rotor and hence the speed of the machine can be controlled from either rotor-or stator-side converter in both super and sub-synchronous speed ranges. At the synchronous speed, slip power is taken from supply to excite the rotor windings and in this case machine behaves as a synchronous machine as shown in Fig.2. The mechanical power and the stator electric power output are computed as follows

$$Pr=Tm*\omega r \qquad (1)$$

$$Ps=Tem*\omega s \qquad (2)$$

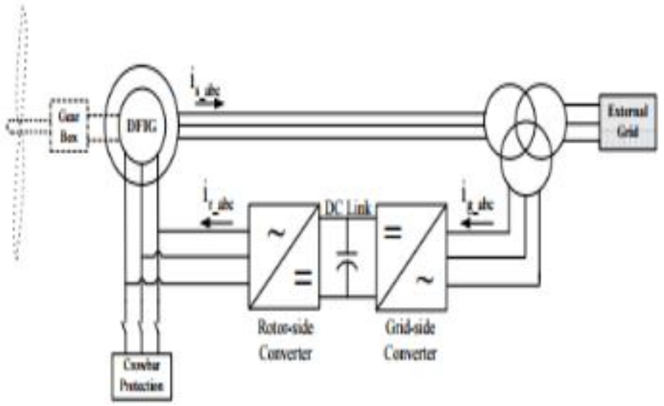

Fig.2. Typical DFIG-based wind turbine system.

For a loss less generator the mechanical equation is

$$J\ (d\omega r/dt) = Tm-Tem \qquad (3)$$

In steady-state at fixed speed for a loss less generator

$$Tm=Tem \ \text{and} \ Pm=Ps+Pr \qquad (4)$$

And it follows that:

$$Pr=Pm-Ps=Tm\ \omega r-\ Tem*\omega s = -S\ Ps \qquad (5)$$

Where $S=(\omega s-\ \omega r)/\ \omega s$ is defines as the slip of the generator.

B. Back-to-Back AC/DC/AC Converter Modeling

Mathematical modeling of converter system is realized by using various types of models, which can be broadly divided into two groups, mathematical functional models and Mathematical physical models (either equation-oriented or graphic-oriented, where graphic-oriented approach is actually based on the same differential equations).

III. PROPOSED CONTROL SCHEME

Each resonant filter tuned at 6nωs resonant frequency in rotor current controller is capable of rejecting one pair of the positive and negative 6n ± 1 stator harmonic voltages. The proposed rotor current controller is described in Fig. 3 where $R_r, L_r, \sigma, \omega_c, E^1_{rdq}, v^{1*}_{rdq}$ are rotor resistance, rotor inductance, total leakage factor, cutoff frequency, disturbance of rotor back-electromagnetic force, and reference rotor voltage vector in the fundamental reference frame, calculated by

$$v^{1*}_{rdq} = \left(K_p + \frac{K_i}{s} + \sum_{n=1}^{\infty} \frac{K_r \omega_c s}{s^2 + 2\omega_c s + (6n\omega_s)^2}\right) \times \left(i^{1*}_{rdq} - i^{1}_{rdq}\right) + E^{1}_{rdq}. \qquad (6)$$

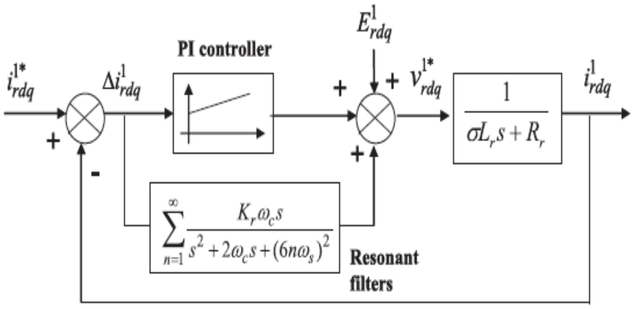

Fig.3. Proposed close d loop PI -R controller.

By adopting the PI-R controller in the fundamental reference frame, it is possible to regulate both of current components in which the dc quantity is controlled by the PI controller whereas the ac harmonic quantities are controlled by an array of resonant filters. The controller gains are designed using Naslin polynomial technique. Once these rotor currents are precisely regulated, a proper stator output voltage of the DFIG (vs) is induced. This voltage will cancel the voltage drop due to nonlinear loads in order to produce a pure sinusoidal stator voltage at the PCC (vPCC) .To improve response of pcc voltage further implemented with fuzzy controller with is we are reducing total harmonic distortion.

IV. SIMULATION RESSULTS

For the sake of simplication, in Simulation tests, only the fifth and seventh harmonics, which are the most severe case, are studied. In this case, the integer value n is equal to one. Fig.4 shows the performance of three phase stator voltage at the PCC and the nonlinear load current. As seen, without any rejection method, this stator voltage becomes distorted with fifth and seventh harmonics due to the nonlinear load current. With the proposed rejection method based on the PI-R controller, these harmonics are fully rejected as shown in Fig. 5. The pure sinusoidal stator voltage waveforms vPCC can be obtained effectively. Fig. 6 shows the rotor current tracking performance of the PI-R controller. It can be observed that the reference currenti1∗rdIs composed of both ac and dc components. The frequency of the ac component is 360 Hz where synchronous frequency of stator voltage is 60Hz. The measured rotor current i1rd is well regulated, and hence the zero steady state current error Δi1rd can be achieved. The pure sinusoidal voltage vPCC after compensation and then on linear load current also are also shown in this Fig.7.

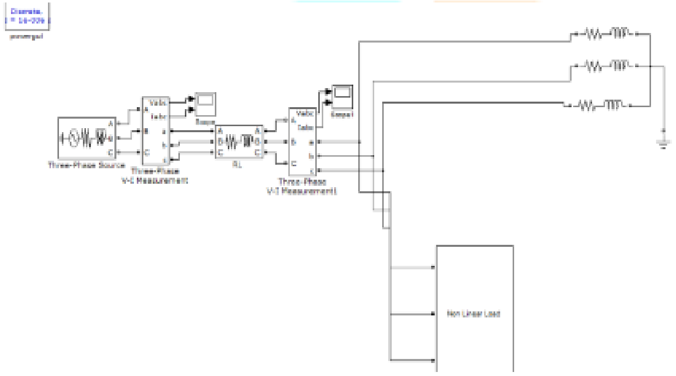

Fig.4. Un Compensated System.

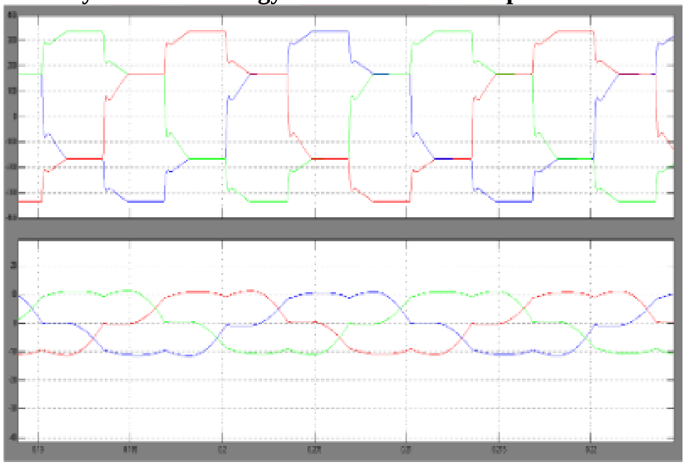

Fig.5. Uncompensated Voltage &Current.

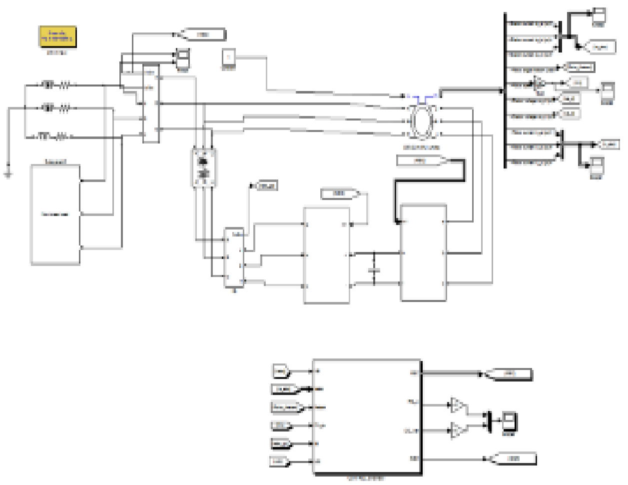

Fig.6. Compensated Voltage &Current Using PI Controller.

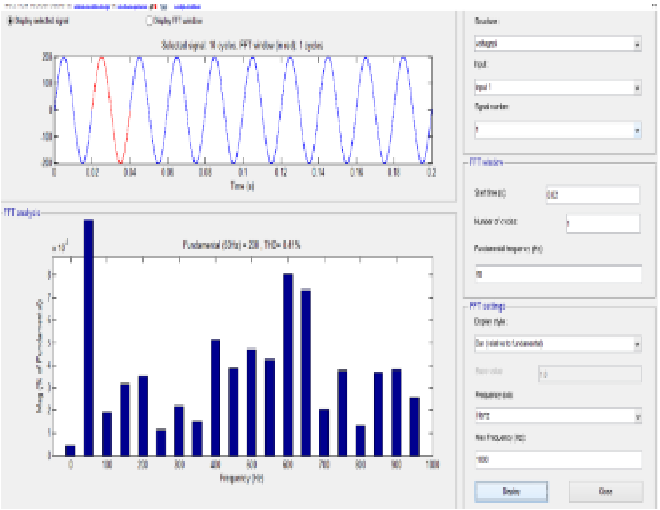

Fig.7. THD.

V. CONCLUSION

A novel 6n ± 1 harmonics rejection method for the tandalone DFIG with nonlinear loads has been proposed. The proposed rejection method is developed based on the PI-R rotor current controller in the fundamental frame. In this frame, each resonant filter adopted in the rotor current controller is capable of rejecting one pair of the positive and negative stator voltage harmonics. The algorithm is totally applicable to the DFIG in term of harmonics rejection, which is clarified by experimental verifications for fifth and seventh harmonic components.

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