An Effective Harmonic Elimination for DFIG Feeding Non-Linear Loads in Stand-Alone Operation

Ngoc-Tung Nguyen*, Hong-Hee Lee**
School of Electrical Engineering, University of Ulsan, South Korea
*nngoctungbk@gmail.com **hhlee@mail.ulsan.ac.kr

Abstract—This paper presents a new control method to compensate the harmonic components in case non-linear loads are connected to the stand-alone Doubly-Fed Induction Generator (DFIG). The load side converter (LSC) operates as an active filter to compensate the harmonics caused by the non-linear loads, and the controller for the active filter is developed by employing a proportional-integral and two resonant controllers in the fundamental reference frame. And also, the stator current is used as the feedback signal for the compensator instead of the load current. In addition, only low pass filter (LPF) is applied in control scheme, so that the control structure becomes simple with easy computation. The effectiveness of proposed compensator is validated by the simulation and experiment.

I. INTRODUCTION

In recent years, the Doubly-Fed Induction Generator (DFIG) has been widely applied to wind energy conversion systems. The most important benefit of the DFIG is the small rate of power converter compared to the nominal power of machine (around 30%), so it can be used in high power applications in both grid and stand-alone mode [1].

In grid operation, most of literatures are focused on the modeling of DFIG, active and reactive power control under either normal or unbalanced grid voltage with different targets and low voltage ride-through (LVRT) capability [2], [3]. On the other hand, in the rural areas or remote villages where the grid is not provided, it is necessary to use DFIG in the stand-alone operation [4]. One of the most serious disadvantages of this operation is the strong influence of unbalanced and non-linear loads to the stator voltage of DFIG. Therefore, the suitable control strategies for DFIG in stand-alone operation should be developed under these abnormal conditions.

In case of the unbalanced load, the balanced stator voltage can be obtained by producing the negative sequence line current of LSC, which has the same magnitude and opposite phase with the corresponding component of load current [5]. Another compensating method for this case is based on the rotor side control (RSC) which generates the harmonic components for the rotor current [6].

Taking into account the non-linear load condition, the configuration of stand-alone DFIG system that feeds the three-phase diode rectifier is shown in Fig. 1. Due to the effect of non-linear load, the stator voltage and current are polluted by the positive \((6n+1)\) and negative \((6n-1)\) order harmonics as analyzed in [10], so that the other loads connected to DFIG are impacted seriously. Therefore, many researchers have been interested in how to eliminate these harmonic components. For aircraft applications, a design method of LC filter which plays a role of a low pass filter to reject these harmonics is introduced in detail [7]. Unfortunately, the power drop on internal resistance and the resonance problem may reduce the efficiency and stability of system. In addition, the control strategies based on either RSC or LSC have been investigated to deal with the harmonic problem. [8] has introduced how to improve the quality of stator current using the current controller in LSC which operates as an active power filter. In this method, the harmonics of line current are generated following the harmonics of load current by using only PI controllers, so the steady-state error for magnitude and phase is not guaranteed. In order to avoid this inconvenience, a resonant controller is employed to eliminate the steady-state error at the selective frequencies for RSC current controller in [9]. In [9], only one single resonant compensator (PI-R) is capable for eliminating one pair of stator voltage harmonics. The harmonics of rotor current is produced to eliminate both fifth and seventh voltage at the point of common coupling (PCC). However, the induced harmonics of rotor current and stator current effect seriously to the rotor as mentioned in [5].

Based on the previous study, this paper proposes a new control algorithm to reject the harmonics of stator current by the LSC control in case non-linear loads are connected to stator side of DFIG. In this control method, the stator current is applied as a feedback signal to the current controller instead of the load current. Thus, the additional current sensors at load side are not needed, so that, the number of current sensors that are installed in system is reduced compared to the previous method in [8]. In the current regulator, one proportional integral and two resonant controllers at six and twelve multiples of synchronous frequency are applied in the fundamental reference frame to eliminate four harmonics, i.e. the fifth, seventh, eleventh and thirteenth harmonic of stator current. The proposed control
method is explained in detail and verified by simulation and experiment.

II. HARMONIC PROBLEMS OF DFIG SYSTEM

In this paper, only mathematical descriptions of DFIG components under non-linear load condition are briefly reviewed, the full harmonic analysis of DFIG system can be searched in [10].

Under non-linear load condition, the harmonics of stator current are generated at the negative \((6n - 1)\) and positive \((6n + 1)\) multiples of synchronous frequency. These harmonic components can be described in corresponding different reference frames which are shown in Fig. 2.

From the full model of DFIG introduced in [10], the harmonics of current/voltage/flux in both stator and rotor are produced. In the stationary reference frame, these vectors can be decomposed into the fundamental and harmonic components:

\[
    F_{αβ}(t) = F_{αβ}(t) + \sum_{n=1}^{∞} \left[ F_{αβ}(6n-1) - (t) + F_{αβ}(6n+1) + (t) \right] = F_{αβ}(t) + \sum_{n=1}^{∞} \left[ j(6n-1)ω_s t + \sum_{n=1}^{∞} F_{αβ}(6n+1) + j(6n+1)ω_s t \right]
\]

In the fundamental rotating reference frame, (1) can be rewritten:

\[
    F_{dq}^1 = F_{dq}^1 + \sum_{n=1}^{∞} F_{dq}(6n-1) + \sum_{n=1}^{∞} F_{dq}(6n+1) + \sum_{n=1}^{∞} F_{dq}(6n-1)e^{-j6nω_s t} + \sum_{n=1}^{∞} F_{dq}(6n+1)e^{j6nω_s t}
\]

It can be inferred from (2) that both negative and positive harmonic components are presented by the ac components that oscillate at the same frequencies of \(±6nω_s\) in fundamental reference frame. It is evident that one resonant controller can be used to control each pair of harmonics.

III. SYSTEM CONTROL

A. Proposed LSC Control

In normal condition, the main function of LSC control is to produce the dc-link voltage and to adjust the input power factor of the front-end converter. The fundamental component of \(d\)-axis of line current is responsible for the former whereas the \(q\)-axis of line current is applied for the latter. These components are adjusted by the PI controller, which are given by

\[
    \begin{align*}
    i_{dq}^* &= \left( \frac{K_P}{s} + \frac{K_I}{s} \right)(V_{DC} - V_{DC}) \\
    i_{q0} &= 0
    \end{align*}
\]

Under non-linear load condition, the LSC control is also responsible to produce the sinusoidal stator current. For this purpose, the LSC is controlled as an active power filter to generate the harmonics of line current to eliminate the harmonics of stator current.

The stator current is the sum of load current and line current, as illustrated in Fig. 3. These current can be expressed in fundamental reference frame as

\[
    i_{sd} = i_{ldq} + \frac{i_{dq}}{k}
\]

Decomposing into fundamental and harmonic components, (4) can be rewritten as

\[
    \begin{align*}
    i_{sd0} &= i_{ld0} + \frac{i_{d0}}{k} \\
    i_{sdh} &= i_{ldh} + \frac{i_{dh}}{k}
    \end{align*}
\]

As can be seen from (6), the harmonic components of stator current can be eliminated by producing the harmonic line current of LSC. The overall method to achieve the zero harmonic stator current is to generate the line current which has same magnitude but opposite phase to the load current for each harmonic component. Therefore, the reference line current is given as below:

\[
    i_{dq_{err}} = K_P + \frac{K_I}{s}
\]
\[
\begin{cases}
    i_{dh}^* = -k \sum i_{d_{dh}} \\
    i_{qh}^* = -k \sum i_{q_{qh}}
\end{cases}
\]  \hspace{1cm} (7)

In order to apply (7) to the practical controller, the load current must be measured, and the additional current sensors increase the cost of system. To avoid this inconvenience, it is necessary to remove the load current from the controller. For this purpose, the reference value for harmonics of line current is inferred from (6) and (7):

\[
\begin{cases}
    i_{dh}^* = -k \sum i_{d_{dh}} = i_{dh} - k i_{sdh} \\
    i_{qh}^* = -k \sum i_{q_{qh}} = i_{qh} - k i_{sqh}
\end{cases}
\]  \hspace{1cm} (8)

Next, the errors between total component value of line current and its measured value are expressed from (6) and (8):

\[
\begin{align*}
    i_{d_{err}} &= i_d^* - i_d = (i_{d_{err}} + i_{d_{ih}}) - i_d \\
    &= i_{d_{err}} + (i_{dh} - k i_{sdh}) - i_d \\
    &= i_{d_{err}} - k i_{sd} + (k i_{sd0} - i_d) \\
    i_{q_{err}} &= i_q^* - i_q = (i_{q_{err}} + i_{q_{ih}}) - i_q \\
    &= i_{q_{err}} + (i_{qh} - k i_{sqh}) - i_q \\
    &= -k i_{sq} + (k i_{sq0} - i_q)
\end{align*}
\]  \hspace{1cm} (9)

In (9) and (10), \( i_{d_{err}} \) and \( i_{q_{err}} \) are the reference values of the fundamental component of line current in \( d \)- and \( q \)-axis, respectively. These values are evaluated by using (3). The dc components \( (k i_{sd0} - i_{d0}) \) and \( (k i_{sq0} - i_{q0}) \) can be achieved through a LPF from the corresponding terms of stator and line current, i.e. \( (k i_{sd} - i_d) \) and \( (k i_{sq} - i_q) \), respectively. Only one LPF is used for each term to minimize the impact of the filters such as error and delay time, so that, the accuracy of the controller is guaranteed. In addition, the LPF is designed for not only rejecting high frequency components but also reducing errors and delay time at the transient time. Thus, the cut-off frequency is assigned at 20Hz. The discrete transfer function of this LPF is given by

\[
G(z) = \frac{0.0009278 \times (1 + 2z^{-1} + z^{-2})}{1 - 1.87816z^{-1} + 0.88187z^{-2}}
\]  \hspace{1cm} (11)

As can be seen from (10), the inputs of current controller consist of two aforementioned dc components and the stator current which contains its harmonic components. From (2), these components have the frequencies of \( 6n \) multiples of synchronous frequency \( (n = 1, 2, 3 \ldots) \). Therefore, the current controller for line current given in (9) and (10) should be designed to assure the zero error at steady-state of both dc and harmonic components. The dc component is regulated by the PI controller, whereas each harmonic component can be rejected by the resonant controller with the corresponding resonant frequency. Because the total component of stator current is employed directly to the regulator, so the higher order harmonic frequencies can be adjusted without error extraction process. In this method, the \( 6^{th} \) and \( 12^{th} \) order harmonic components \( (n = 1, n = 2) \) are chosen to be regulated by the resonant controllers. Thus, the proportional

![Fig. 5. Proposed LSC control method.](image-url)
integral plus two resonant controllers (PI-2R) which is shown in Fig. 4 are used in the regulator.

The proposed LSC control method is totally shown in Fig. 5. In this control scheme, one PI-2R controller is used for d- and q- axis to control the dc-link voltage as well as power factor and the induced harmonics of line current. Only one LPF is applied to control each component, so the control structure becomes simple with easy computation.

**B. RSC Control**

In stand-alone application, the main role of RSC control is to regulate the magnitude of stator voltage as desired value and the active power delivered to loads. In this paper, the compensation for harmonic problem is done by the LSC, so the control of RSC is generally same as the conventional control method presented in [4].

In this control method, the d- axis rotor current is responsible for directly controlling the magnitude of stator voltage to follow the command value. Because the stator voltage is polluted with high order harmonic components under non-linear load condition, it is necessary to reject all of high frequency components included in stator voltage to improve the accuracy of rotor current control loop. In this paper, two low-pass filters (LPF) with a proper cut-off frequency are used for d- and q- axis of stator voltage to get their dc components. Finally, the magnitude of stator voltage is expressed by

$$|v_s| = \sqrt{\left(v_{sd}\right)^2 + \left(v_{sq}\right)^2}$$  \hspace{1cm} (12)

Fig. 6 shows the RSC control algorithm with the modified magnitude stator voltage for the non-linear load compensator.

In order to verify the effectiveness of proposed control method, both simulation and experiment are carried out. The simulation is conducted with the configuration given in Fig.1. A dc motor is used as the wind turbine emulator to force the DFIG rotate around the synchronous speed. A three-phase diode rectifier which is used to supply for a resistance load is connected to stator side through SW1; another three phase resistance load is connected directly to stator. In simulations, the dc-link voltage and magnitude of stator voltage are kept constant at 200V; the stator frequency is controlled at 50Hz.

At first, the impact of non-linear load is tested without the compensating method. As seen in Fig. 7 from top to bottom, the stator current is distorted with high THD factors because of the non-linear load current whereas the line current is nearly sinusoidal, and hence, the stator voltage is also polluted. The steady-state performances of the proposed compensating method with the same sequential order with those in Fig. 7 are illustrated in Fig. 8. By clear comparison between these waveforms, the proposed method performs the better results with lower THD factor in both stator current and voltage. For the purpose of further comparison, the FFT analysis of stator current and voltage in fundamental reference frame without and with developed algorithm are given in Figs. 9 and 10. It can be apparently seen that the magnitude of both stator current and voltage at 300Hz (6th order) and 600Hz (12th order) are significantly reduced. It is evident that the introduced strategy has ability to eliminate the harmonic components at 6th and 12th order under non-linear load condition.

**V. EXPERIMENTAL RESULTS**
To confirm the effectiveness of proposed control method, the experiment implementation is also carried out with the hardware setup shown in Fig. 11. The LSC and RSC are fed by an IGBT-based PWM front-end converter and inverter, respectively. Both of them are controlled by a control board of DSP TMS320F28335 of Texas Instruments with the switching frequency at 5 kHz. In addition, another DSP board is tuned to regulate the speed of DC motor which plays the role of a prime mover.

Figs. 12(a) and 13(a) show the waveforms of stator current, non-linear load current and line current from top to bottom without and with compensating method, respectively. As shown in Fig. 12(a), because no elimination method is operated, the stator current is seriously distorted by receiving the harmonics of load current, and the line current is almost sinusoidal. In contrast, as shown in Fig. 13 (a), the harmonics of line current are generated to compensate those of load currents, so the stator current becomes nearly sinusoidal with low distorted components.

VI. CONCLUSIONS

This paper has presented a new control approach for stand-alone DFIG system under non-linear load condition. In this method, the stator current is directly employed for the controller to remove the additional current sensors in load side in case non-linear loads are connected to stator of DFIG. The control method is simplified by applying the LPF to the current regulator. Thus, higher order harmonics can be eliminated without any extra filter. In addition, two resonant controllers are used as current regulator to eliminate effectively four harmonics at the 5th, 7th, 11th and 13th order of stator currents. As a result, the quality of stator voltage and current is improved much better. The simulation and experimental results are matched each other and evaluate the effectiveness of the proposed compensating method.

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