Enhanced Control of a DFIG-Based Wind-Power Generation System With Series Grid-Side Converter Under Unbalanced Grid Voltage Conditions

Peetha Vishnu Raju*[1] : Ibrahim Shaik[2] : Dr. Abdul Ahad[3]

[1]M.tech (P.S) Student Department Of EEE, Nimra College Of Engineering & Technology

[2] Asst. Professor Department Of EEE, Nimra College Of Engineering & Technology

[3]Professor & Head Of The Department, Nimra College Of Engineering & Technology

ABSTRACT: This paper presents an enhanced control method for a doubly fed induction generator (DFIG)-based wind-power generation system with series grid-side converter (SGSC) under unbalanced grid voltage conditions. The behaviors of the DFIG system with SGSC during network unbalance are described. By injecting a series control voltage generated from the SGSC to balance the stator voltage, the adverse effects of voltage unbalance upon the DFIG, such as stator and rotor current unbalances, electromagnetic torque, and power pulsations, can be removed, and then the conventional vector control strategy for the rotor-side converter remains in full force under unbalanced conditions. Meanwhile, three control targets for the parallel grid-side converter (PGSC) are identified, including eliminating the oscillations in the total active power or reactive power, or eliminating negative-sequence current injected to the grid. Furthermore, a precise current reference generation strategy for the PGSC has been proposed for the PGSC to further improve the operation performance of the whole system. Finally, the proposed coordinated control strategy for the DFIG system with SGSC has been validated by the simulation results of a 2-MW-DFIG-based wind turbine with SGSC and experimental results on a laboratory-scale experimental rig under small steady-state grid voltage unbalance.

INTRODUCTION

The main reason causing stator and rotor current unbalances, electromagnetic torque, and power pulsations in the DFIG is stator voltage unbalance: if the negative-sequence voltage at the generator's stator terminal can be eliminated and only balanced positive-sequence voltage is left during network unbalance, the adverse effects of unbalance upon the DFIG will be removed naturally. More recently, a new DFIG configuration with an additional grid-side converter in series with the generator's stator windings has been proposed by Flannery and Venkataramanan in order to tackle the low-voltage ride-through (LVRT) operation. As the stator terminal voltage can be flexibly controlled by regulating the output voltage of series grid-side converter (SGSC), the DFIG can effectively cope with various deep voltage sag conditions by suppressing or eliminating the transient dc and negative-sequence flux components, and the excellent LVRT operation performance has been validated by using simulation and experiment tests during symmetrical or unsymmetrical grid faults. Unlike other LVRT method using a series dynamic voltage restorer (DVR) mentioned in the DFIG system with SGSC can also cope with the case of long-term steady-state grid voltage unbalance. Considering that small grid voltage unbalances (including both steady-state and transient grid-voltage unbalance) occur more frequently than severe voltage dips, an improved control scheme is employed to further extend the applications of the new DFIG system with SGSC in. By coordinately controlling the SGSC, PGSC, and RSC, three selective control targets for PGSC are obtained to enhance the unbalanced operation capability. Meanwhile, the VA ratings and power losses of the SGSC and the series transformer have also been calculated and analyzed by the authors. However, the proposed positive- and negative-sequence *dq*-axis reference components of the PGSC's currents are deduced by assuming that PGSC's reactive power being zero during network unbalance and only simulation results are given.

Taking into account the fact that PGSC has flexible control capability, some reactive power generated from the PGSC can be delivered into the grid, which means that the PGSC can participate in the auxiliary reactive power regulation during the network unbalance.

Consequently, it is necessary for the PGSC to provide the required reactive power support to the grid; thus, accurate current reference generation should be achieved for the PGSC enhanced control.

OPERATION BEHAVIOR OF DFIG SYSTEM WITH SGSC DURING NETWORK VOLTAGE UNBALANCE:SGSC: In order to counteract the effect of the negative-sequence grid voltage, a series compensation voltage vector generated by the SGSC is injected to balance the stator voltage. Due to the existence of the series transformer impedance, there is still a slight difference between the positive-sequence grid voltage and DFIG stator voltage. Consequently, a positive-sequence voltage vector should be injected to compensate the impedance voltage drop, making the stator voltage keep in line with the positive-sequence grid voltage.

As the stator currents of the DFIG are symmetrical by balancing the generator stator terminal voltage, the currents flowing into SGSC through the series transformer are also balanced, which are equal to the positive-sequence stator currents of DFIG.

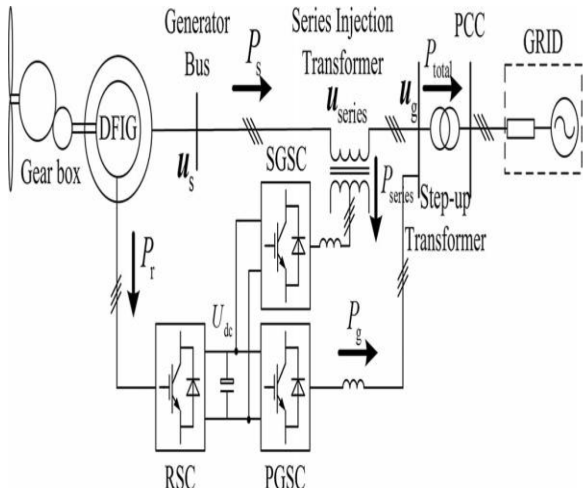


Fig. 1 Configuration of the DFIG system with SGSC.

As analyzed in, under unbalanced network conditions, the instantaneous active and reactive power flowing through the SGSC contain average dc components and double-supply frequency oscillations, which can be represented as

Pseries = Pseries av + Pseries cos2 cos 2ωt + Pseries sin2 sin 2ωt

Qseries = Qseries av+Qseries cos2 cos 2ωt+Qseries sin2 sin 2ωt

where

$$\begin{bmatrix} P_{\text{series\_av}} \\ Q_{\text{series\_av}} \\ P_{\text{series\_cos2}} \\ P_{\text{series\_sin2}} \\ Q_{\text{series\_cos2}} \\ Q_{\text{series\_sin2}} \end{bmatrix} = \begin{bmatrix} u^{+}_{\text{comd}+} & u^{+}_{\text{comq}+} \\ u^{+}_{\text{comq}+} & -u^{+}_{\text{comd}+} \\ -u^{-}_{gd-} & -u^{-}_{gq-} \\ -u^{-}_{gq-} & u^{-}_{gd-} \\ -u^{-}_{gq-} & u^{-}_{gd-} \\ u^{-}_{gd-} & u^{-}_{gq-} \end{bmatrix} \cdot \begin{bmatrix} i^{+}_{sd+} \\ i^{+}_{sq+} \end{bmatrix} \quad (2)$$

where and are the positive- and negative-sequence voltage errors that need to be compensated, respectively. As can be seen from (2), although there are null oscillations in generator's power output, the double-supply frequency pulsations in SGSC's active and reactive power still exist due to the interaction between the negative-sequence grid voltages and positive-sequence stator currents, which lead to the oscillations of total power output. Furthermore, the oscillating active power from the SGSC is delivered into the dc-link capacitor, which produces the pulsations in dc-link voltage.

B. PGSC

Considering that the PGSC is directly connected to the grid, its operation behavior is similar to a grid-connected voltage-source converter system. The active and reactive power from the PGSC to the grid can be expressed as

$$P_g = P_{g\_av} + P_{g\_sin2}\sin 2\omega t + P_{g\_cos2}\cos 2\omega t$$
$$Q_g = Q_{g\_av} + Q_{g\_sin2}\sin 2\omega t + Q_{g\_cos2}\cos 2\omega t \quad (3)$$

where

$$\begin{bmatrix} P_{g\_av} \\ Q_{g\_av} \\ P_{g\_cos2} \\ P_{g\_sin2} \\ Q_{g\_cos2} \\ Q_{g\_sin2} \end{bmatrix} = \begin{bmatrix} u_{gd+}^{+} & u_{gq+}^{+} & u_{gd-}^{-} & u_{gq-}^{-} \\ u_{gq+}^{+} & -u_{gd+}^{+} & u_{gq-}^{-} & -u_{gd-}^{-} \\ u_{gd-}^{-} & u_{gq-}^{-} & u_{gd+}^{+} & u_{gq+}^{+} \\ u_{gq-}^{-} & -u_{gd-}^{-} & -u_{gq+}^{+} & u_{gd+}^{+} \\ u_{gq-}^{-} & -u_{gd-}^{-} & u_{gq+}^{+} & -u_{gd+}^{+} \\ -u_{gd-}^{-} & -u_{gq-}^{-} & u_{gd+}^{+} & u_{gq+}^{+} \end{bmatrix} \cdot \begin{bmatrix} i_{gd+}^{+} \\ i_{gq+}^{+} \\ i_{gd-}^{-} \\ i_{gq-}^{-} \end{bmatrix}. \quad (4)$$

$$\frac{1}{2}C\frac{du_{\mathrm{dc}}^2}{dt} = P_r + P_{\mathrm{series}} - P_g.$$

As derived from (4) and (5), similar to the case illustrated by (2), the power exchanges between the PGSC and grid contain active and reactive power oscillating at a double grid frequency, which further aggravates the pulsations in dc-link voltage and deteriorating the qualities of output powers.

C. RSC:By eliminating the negative-sequence stator voltage, the stator terminal voltages of DFIG are balanced during network unbalance. Thus, the conventional vector control strategy or the direct power control (DPC) scheme for the RSC remains in full force under unbalanced grid voltage conditions. With effective control of SGSC, the adverse effects of voltage unbalance upon DFIG such as large stator and rotor current unbalances, electromagnetic torque and power pulsations will be eliminated simultaneously, viz.

$$i_{s-} = 0, \quad i_{r-} = 0, \quad T_{e\sin 2} = T_{e\cos 2} = 0$$
$$P_{s\sin 2} = P_{s\cos 2} = 0, \quad Q_{s\sin 2} = Q_{s\cos 2} = 0$$
$$P_{r\sin 2} = P_{r\cos 2} = 0, \quad Q_{r\sin 2} = Q_{r\cos 2} = 0. \quad (6)$$

As the operation and control of RSC under normal condition have been well investigated in numerous literature works, it will be not discussed in detail in this paper.

COORDINATED CONTROL OF SGSC, PGSC, AND RSC

A. SGSC

As mentioned in the main task of the SGSC during network unbalance is to keep the DFIG stator voltage always in line with the positive-sequence grid voltage; thus, the SGSC can be controlled to achieve the following control target:

$$u_{s+} = u_{g+}$$
$$u_{s-} = 0. \quad (7)$$

In order to meet the demand of (7), positive-sequence component of stator terminal voltage vector should be controlled to equal to that of grid voltage vector, while negative-sequence component of stator voltage vector should be controlled to zero.

B. PGSC

Under unbalanced grid voltage conditions, there are four grid current components, i.e., ,

and can be controlled to improve the system performance. Therefore, for the PGSC, apart from the average grid-side active and reactive powers

and , shown in (4), there are two more power oscillating terms that can be controlled.

The PGSC may be controlled to achieve one of the following control targets.

- Target 1: to reduce the oscillations of the whole DFIG system's total active power entering the grid;

- Target 2: to eliminate the oscillations of the whole DFIG system's total reactive power entering the grid;
- Target 3: to suppress the whole system's negative-sequence currents injected to the grid.

Target 1: As shown in Fig. 1, based on (1), (3), and (6), the total active power of the DFIG system with SGSC can be expressed as

C. RSC

For RSC, as the stator terminal voltage of DFIG is still balanced during network unbalance, the conventional VC strategy or the DPC strategy can remain in full force.

D. VC System for the SGSC and PGSC

Under steady-state unbalanced grid voltage conditions, the grid voltages and stator voltages can be referred to two synchronous *dq* reference frames rotating at and , respectively. Double-supply frequency oscillations in voltage components are produced when positive/negative-sequence voltages are transformed to *dq*-axes rotating in the opposite direction. Consequently, notch filters tuned at 2 are used to suppress the pulsation components oscillating at the double power supply frequency, and dc components can be obtained by decomposing the stator and grid voltages. To achieve the goal of (7), the positive- and negative-sequence SGSC control voltages shown in Fig. 2 can be represented in the dual synchronous rotating reference frames as

$$\begin{cases} u^{+}_{seriesdq+} = \left(K_{p1+} + K_{i1+}/s\right)\left(u^{+}_{gdq+} - u^{+}_{sdq+}\right) \\ u^{-}_{seriesdq-} = \left(K_{p1-} + K_{i1-}/s\right)\left(0 - u^{-}_{sdq-}\right) \end{cases}$$

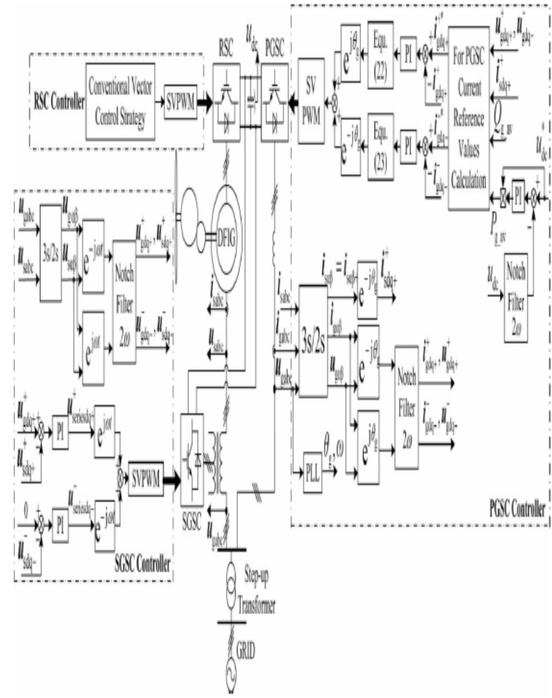
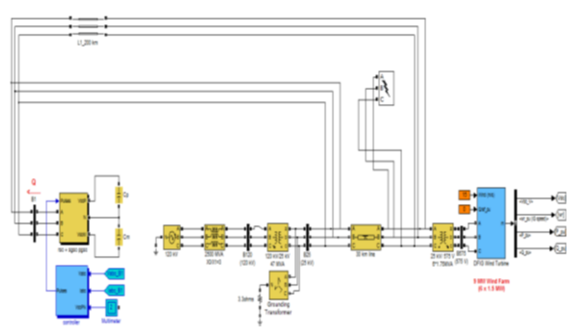
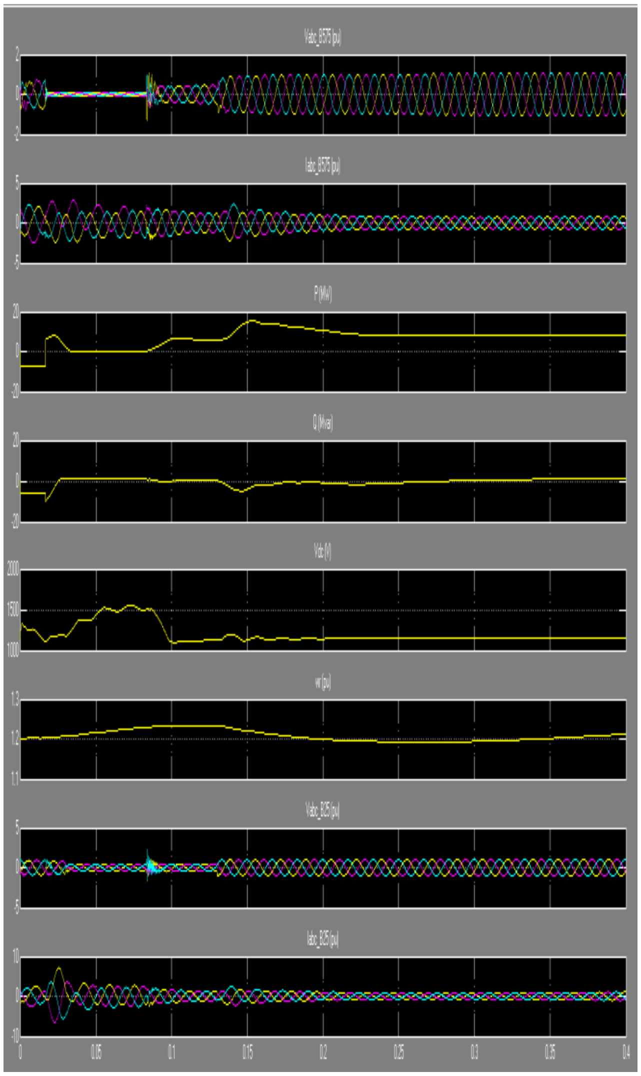


Fig. 2. Schematic diagram of the proposed control scheme for the DFIG system with SGSC.

SIMULATION STUDIES

For evaluation of the proposed control strategy, simulations on a 2-MW DFIG wind turbine with SGSC have been conducted by using MATLAB/Simulink. Details of the simulated DFIG system are given. Both PGSC current and SGSC voltage PI controller parameters are optimized by using the traditional root locus method and are listed in Table I. A single-phase resistive load at the primary side of the step-up transformer is used to generate the voltage unbalance.





CONCLUSION

Enhanced control of a grid-connected DFIG-based wind turbine with SGSC under unbalanced grid voltage conditions has been investigated in this paper. The precise current reference generation strategy for the PGSC has been proposed, and a coordinated control strategy for the SGSC, PGSC, and RSC is discussed. Three selective control targets for PGSC including eliminating the oscillations in the total active power or reactive power, or generating total balanced current from the whole system have been obtained, respectively, by coordinating control of the PGSC and SGSC, while the RSC is controlled with the conventional VC strategy to achieve the goals of zero oscillations in DFIG's active and reactive power and balanced stator and rotor currents in the three-phase windings under unbalanced voltage conditions. Furthermore, the function of SGSC need not be changed during both the normal grid condition and the unbalanced voltage condition for the three control strategies, and the required dynamic regulation performance can be provided with the proposed dual PI controllers for the SGSC and PGSC. The results show that the enhanced operation and control of the DFIG-based wind-power generation system with SGSC under unbalanced conditions can be significantly improved by eliminating the oscillations in the total active or reactive power, or balancing the total current generated from the overall system.

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Peetha Vishnu Raju: pursuing M.Tech in Nimra College of engineering and technology, Jupudi, Ibrahimpatnam. His specialization in power systems. He graduated in Electrical and Electronics Engineering from Sri Sun Flower College of Engineering & Technology, Lankapalli. Mail ID vishu.peetha@gmail.com

Ibrahim Shaik: is currently working as an ASSISTANT PROFESSOR in Electrical and Electronics Engineering department at Nimra College of engineering and technology (NCET) Jupudi, Ibrahimpatnam. He obtained his M TECH degree in power Electronics And Industrial Drives MAIL ID shaikibrahim75@gmail.com

DR.Abdul Ahad : Mtech. P.hd (NITK) is an eminent PROFESSOR & HEAD OF EEE , nimra group of colleges. he received M.Tech and was conferred Doctorate from NITK SURATKAL. He is expertised in power electronics, power systems, special machines, Electrical machines& industrial applications. He has over a 15 years of teaching experience .He trains various students for various competitive exams like IES ,IAS, GATE , AP GENCO,AP TRANSCO, DISCOMS and no of national competitive exams. He is the chair person of several national and technical symposiums. He published more than 20 international journals and attended several international conferences. His prime interest is in research .to his credit he guided scores of UG AND PG students in their projects and right now he is guiding two P,hd scholars.