Power quality and low voltage ride-through capability of induction generator-based wind power generating system

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**POWER QUALITY AND LOW VOLTAGE RIDE-THROUGH
CAPABILITY OF INDUCTION GENERATOR-BASED WIND
POWER GENERATING SYSTEM**

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Summary

Wind energy has become one of the most important clean energy sources all over the world. As compared to fixed speed based wind power generators, the variable speed generators obtain a much higher efficiency. Among the variable speed generators, permanent magnet synchronous generator (PMSG) is one of the commonly used wind power generator but it requires a fully rated back-to-back converter connected to the grid. The doubly-fed induction generator (DFIG) usually obtains the advantages from economic point of view because the converters are equalized to handle 20-30% of the rated power. As a result, DFIG has become one of the most widely used wind power generator nowadays.

However, smaller power rating of the converters also means that the DFIG system has a smaller tolerance to voltage disturbances. When an external fault occurs, the DFIG is required to keep connected to the grid and generate reactive power. Thus, low voltage ride through (LVRT) capability for DFIG is required. However, most of the LVRT methods either loose control of the generator or significantly increase the cost of the DFIG system. Mode switch method is proposed in order to improve the LVRT performance of DFIG. The mode switch DFIG (MSDFIG) switches from the normal operation expand (DF mode) to induction generator mode (IG mode) while a grid fault is detected. In IG mode, the stator side is isolated from the grid and in that case, the transient large current caused by the sudden grid voltage drop can be avoided. Meanwhile, the rotor-side is kept connected to the grid through a back-to-back converter by which the generator is still under control and reactive power could be delivered to the grid. In order to achieve a smooth mode switching, the transient phenomenon of the generator switches from DF mode to IG mode is analyzed and a stator-side crowbar is proposed in order to contain the transient current. The

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resynchronization control of the generator switches from IG mode back to DF mode when the grid voltage is recovered is also developed. Analysis shows that the proposed MSDFIG can smoothly ride through the complete low-voltage and voltage recovery stages. Effectiveness of the scheme is demonstrated through simulation and experiment studies.

The second contribution of this thesis is the harmonic and unbalanced problems analysis and elimination for DFIG. In the stand-alone DFIG system, harmonics and unbalanced components would appear in the voltage at PCC due to nonlinear and unbalanced loads. The distorted voltage would not only reduce the power quality at the PCC, but also be harmful for the generator. On the other hand, while the DFIG is connected in the large grid, the stator current of the generator would be distorted by the nonlinear or unbalanced loads in the grid. In order to improve the power quality and avoid harmful effects on the generator, harmonic and unbalanced components should be eliminated in stand-alone and grid connected DFIGs. Active power filter (APF) is one of the most commonly used method for harmonic elimination but it increases the cost of the DFIG system and also needs an individual controller for the APF. Thus, the compensation control from the rotor-side converter is encouraged recently. The PI controller, PI-resonant (PIR) controller and PI based repetitive controller (PIRC) for harmonic and unbalanced components elimination are analyzed. The effectiveness of PIRC is discussed in great detail and approved by simulation and experimental results.

Unlike conventional power systems, nowadays some of the microgrids adopt DC distribution because of the availability of increasing number of DC output type sources such as photovoltaics and fuel cell and also loads such as laptops, computers, LED, lightening etc. In the conventional connection between the DFIG and DC microgrid (DCMG) requires a fully rated converter to transfer the AC power generated from the

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generator into the DCMG. In that case, the cost of DFIG would significantly increase and lose its benefits from economic point of view. A new scheme of DFIG is proposed in which the stator windings are connected to the DCMG through a three phase diode rectifier and the rotor windings are still connected to a rotor-side converter. Compared to the conventional scheme, the proposed configuration of DFIG saves the fully rated converter. But the stator-side rectifier would introduce distorted stator voltages which are uncontrollable and as a result, harmonic components would appear in the stator current. The current injected into the DCMG would also be distorted. In order to eliminate the harmonics in the stator current, PIRC is applied in the controller of rotor-side converter. For the DC current, the harmonic components are proposed to be eliminated by a harmonic compensator which is controlled by PIRC. Simulation and experimental results verify that the PIRC could effectively reduce the harmonics in both the stator currents and DC current. Meanwhile, in order to improve the efficiency of the system, the DFIG is controlled by maximum power point tracking (MPPT) and a battery energy storage system (BESS) is proposed to smooth the power flow and better load sharing under droop control.

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List of Abbreviations

BESS	Battery Energy Storage System
BPF	Band-Pass Filter
CB	Circuit Breaker
CSG	Converter of Synchronous Generator
DC	Direct Current
DCMG	DC-Microgrid
DF	Doubly-fed
DFIG	Doubly-fed Induction Generator
DG	Distributed generator
GSC	Grid-side Converter
IG	Induction Generator
IMP	Internal Mode Principle
LSC	Load-side Converter
LVRT	Low Voltage Ride Through
MG	Microgrid
MPPT	Maximum Power Point Tracking
MSDFIG	Mode Switching Doubly-fed Induction Generator
PCC	Point-of-Common Coupling
PI	Proportional-Integral
PIR	PI control schemes with Resonant loops
PIRC	Repetitive PI Control
PMSG	Permanent Magnetic Synchronous Generator
RC	Repetitive Control
RSC	Rotor-side Converter
SC	Super Capacitor
SOC	State of Charge
SSC	Stator-Side Crowbar
SSR	Stator-Side Rectifier

Chapter 1. Introduction

The research efforts on the renewable and clean energy generation systems are receiving increasing attention globally. As one of the most attractive renewable energy sources, wind energy is well known for its low cost, high energy density and low pollution operational characteristics. It is expected that the penetration of wind power around the world will reach 12% by 2020 and the wind power generation will continually contribute to the global energy production in the future [1].

Constant speed and variable speed wind power generators are two types of main generators used in wind farms. For effective harnessing of wind power, variable speed constant frequency generators (VSCFGs) are always favored. Among variable speed constant frequency generators, permanent magnet synchronous generator (PMSG) is widely used in small wind farms but it requires a fully rated converter with a high cost. As one of the VSCFGs, DFIG is used extensively because of the following advantages.

- Low cost. Because the power converter of the DFIG only handles 20% to 30% of the total power, therefore DFIGs are more attractive from an economical point of view.
- High efficiency. Because of the power rating of the converters of DFIG is much lower than that of other generators, the power loss of the converter is much smaller and the power efficiency is higher.
- Larger power capacity. Because of the DFIG is self-excited generator, the power capacity can be much higher than that of PMSG with the same cost.

DFIG is controlled by a back-to-back converter. There are two modes of connection of DFIGs, grid-connection mode and stand-alone mode. The stator side is connected to the grid or loads in grid-connected or stand-alone mode, respectively. The rotor side is connected to a back to back converter. Figure 1-1 shows the fundamental schemes of grid-connected and stand-alone DFIGs. In the stand-alone DFIG, the load-side converter (LSC) is controlled to maintain the DC link voltage and the rotor-side converter (RSC) for stator voltage and reactive power control to supply the loads. In the grid-connected DFIG, the GSC is controlled for the regulation of DC link voltage and RSC is controlled for MPPT and stator-side reactive power support.

Figure 1-1 Typical configuration of (a) stand-alone DFIG, (b) grid connected DFIG

1.1 Introduction of low voltage ride-through (LVRT) for DFIGs

As aforementioned, DFIGs are more attractive from an economical point of view and extensively used because the power converter of the DFIG only handle 20% to 30% of the total power. But unfortunately, the smaller power rating of the converters also means that the DFIG system has a smaller tolerance to voltage disturbances. In grid-connected mode, when an external fault occurs, the abrupt stator voltage sag would produce a dc component in the stator flux which appears as an oscillatory electromagnetic field in the rotor circuit. Severe voltage sag could lead to large outrush current on both the stator and rotor circuits, consequently the current can overload the converters. On the other hand, grid codes require the generator to remain connected to the grid during the fault [2]. So far, many LVRT approaches have been proposed in the literatures [3-7].

All the proposed LVRT approaches can be divided into two types. First one is the modification of the software, like improving the control scheme of the DFIG to enhance the LVRT performance [8, 9]. And the second one is changing the configuration of DFIG, like adding a series connected compensation device at the stator-side of DFIG to compensate the voltage during grid fault conditions [7, 10, 11].

A MSDFIG scheme is proposed for the purpose of achieving low voltage ride-through for wind turbines [12]. The MSDFIG operates as a DFIG under normal condition but upon the detection of a low-voltage incident, the generator is to smoothly transfer to IG mode through the switching in of a set of stator-side crowbar. A new strategy on the control of the crowbar resistance is proposed. The MSDFIG automatically reverts back to the DFIG mode when network voltage recovers.

Analysis shows that the proposed MSDFIG scheme can ride through the complete low-voltage and voltage recovery stages. Effectiveness of the scheme is demonstrated through simulation and experiment studies.

1.2 Introduction of distorted and unbalanced stator voltage compensation of stand-alone DFIG

When the DFIG is operated in the stand-alone mode, the voltage at the PCC is maintained by controlling the RSC of DFIG [9]. The stand-alone generator system will have to operate with nonlinear and unbalanced loads connected to it. Such loads draw distorted or unbalanced currents which will result in distorted and unbalanced voltages at the stator terminals of the generators. The negative phase sequence component of the unbalanced stator voltage would induce electromagnetic torque pulsations and excessive heat in the generators. Efficiency of the generators is degraded and the performance of other loads will be affected. Therefore, it is desirable to eliminate the negative phase sequence and harmonic components of the stator voltage in order to overcome such deficiencies.

In [13], the harmonic load current is compensated by using a traditional PI controller designed based on the synchronous reference frame. However, the PI controller has small gains at the harmonic frequencies. Therefore, the effectiveness of this method is limited. Alleviation of similar voltage quality problems using PI controllers based on harmonic reference frames has been proposed in [14]. In these methods, the stator voltage is transformed into the synchronous reference frame and the negative phase sequence [14] and harmonic [15] components respectively are extracted using band-pass filters (BPFs) and then transformed into their corresponding

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reference frames. Unfortunately the methods require large amount of calculations. Alternatively, PIR control has been proposed in [6, 16, 17]. Two resonant loops are required for each of the $6n \pm 1$ ($n=1,2,\dots$) order harmonic components. The unbalanced component is also eliminated along with the 5th and 7th harmonic components [18] using the PIR controllers, but the elimination of the unbalance component requires another resonant loop. Consequently, the main drawback of PIR controller is that each resonant loop can only damp the harmonic component corresponding to its resonant frequency.

An alternative approach for harmonic elimination is to use RC method [19-23]. The RC presents large gain at integer multiples of the fundamental frequency and is well known for its effectiveness in controlling harmonics [20]. It has been proposed in [16] to reduce the current harmonics of a DC/AC inverter using a hybrid scheme which combines PI and RC techniques. However, it has yet to be extended for the case of stand-alone DFIGs. In Chapter 3, the proposed PIRC scheme is to eliminate the unbalance and harmonic components of the stator voltage of a stand-alone DFIG. In synchronous reference frame, the fundamental components of the stator voltage are regulated by PI controllers while the unbalance and harmonic components are eliminated through the application of RC technique.

1.3 Introduction of research on DC-microgrid connected with DFIGs

DG systems like wind turbines, photovoltaics and fuel cells are increasingly installed in utility grids presently [24-29] but it introduces problems like unstable voltage, current harmonics and frequency vibration. As a result, microgrids (MGs) are

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researched extensively in order to solve problems like voltage variations and protection issues when large amount of DGs are connected to the grid. It is envisaged that DC microgrids (DCMGs) will be used immensely in future because of significant amount of DC loads and increasing number of DC output type sources such as photovoltaics, fuel cells and batteries are installed into the grid [30, 31].

Doubly-fed induction generator is one of the most commonly used wind power generators over the world but it is not so widely used in DC-microgrids. The advantages of DFIGs are summarized in Section 1.1. But when the DFIG is connected to a DCMG, a converter with full power rating is required in the conventional configuration to transfer AC power generated by DFIG to DCMG. Comparing with PMSG that connected in DCMG, the advantages of DFIG will be disappeared. To overcome this shortcoming, it is proposed in this study that a stator-side rectifier (SSR) be installed between the stator and the DCMG so that the cost of the DFIG system can be kept to a low value. With this configuration, harmonics appear on both the stator currents and stator power in the proposed DFIG configuration because of SSR. It is proposed in this research that the stator current harmonics are compensated using control of RSC and an additional supercapacitor (SC) interfaced with DCMG is used for stator power harmonic elimination. Compared with PI [32] and PI-R control [33, 34], repetitive control (RC) technique that requires a low calculation burden is proposed in the control of SC to eliminate the harmonics in the DC side of SSR.

The efficiency of the generator is another concern when it is connected to the DCMG. If the DFIG is controlled to maintain the voltage in a small system or in stand-alone conditions, the output power of the DFIG will be determined by the loads and the maximum power point tracking (MPPT) cannot be done anymore. As a result,

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the efficiency of the DFIG will be decreased. It is proposed in this paper that a battery energy storage system (BESS) is interfaced to the DCMG for the purpose of power buffering. In such a case, the grid voltage can be maintained with the control of BESS and the DFIG would be able to perform MPPT in order to achieve a greater efficiency.

BESS has a limited capacity so that if the load sharing is unequal, the BESS can be easily fully charged or discharged in some nodes with lighter or heavier loads respectively. In order to prevent this situation, an improved droop control is applied in the control of BESS for the purpose of equitable load sharing and stable DC voltage. Even though an improved droop control has been discussed in [35], it needs further modifications when a DFIG is installed in the DCMG. In order to improve the reliability of the system, when the BESS is fully charged or out of service due to fault conditions, the DFIG will be switched to a control mode where the local DC voltage is regulated to achieve DC voltage droop control. With this proposed control, the system can be kept stable even the BESS is out of service.

1.4 Main contribution of the thesis

The main contribution of this research work could be summarized as follows.

First of all, in order to improve the LVRT performance of DFIG, an improved MSDFIG is proposed in Chapter 3. Two modes of DFIG connection are discussed. In MSDFIG, the generator is in normal operation like conventional DFIG and works in DF mode. Once a grid voltage drop is detected, the generator will be converted to IG mode in which the stator windings are isolated from the large grid. Thus, the voltage drop on the large grid will not affect the generator.

In the proposed MSDFIG, the smooth mode switching is achieved by the control of SSC. After the DFIG is switched to IG mode, it will continue generating real power and at the same time, reactive power is also regulated by control of RSC to supply the grid during grid fault condition.

The DFIG will be switched back to DF mode after the grid voltage is recovered. In order to achieve a smooth mode switch, the control of DFIG will be switched to synchronous mode to control the stator voltage. Once the stator voltage gains the required amplitude, phase and sequence of the grid voltage, the stator can be connected to the grid and the DFIG will be back to DF mode under normal control. Thus, the LVRT of DFIG can be achieved smoothly.

The second main contribution of the research work is the harmonic elimination of DFIG using the RC. Harmonic problems in both stand-alone and grid-connected DFIG are analyzed.

In stand-alone DFIG, harmonic and unbalanced components may be present in the stator voltage and current when some non-linear or unbalanced loads are connected at the PCC. The power quality at the PCC will be significantly depraved by the harmonics.

While for the grid-connected DFIG, the distorted grid voltage would lead to harmonic or unbalanced components in the stator current. The harmonic current is harmful for the DFIG and therefore, harmonics need to be eliminated.

RC technique is applied for the elimination of harmonic and unbalanced components in stator voltage of stand-alone DFIG and stator current of grid-connected

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DFIG. Compared with the harmonic control methods introduced in previous literatures, the advantages of the proposed RC can be summarized as follows:

- Both unbalanced and harmonic components shall be eliminated using the same proposed controller. Therefore the proposed control scheme imposes much less computational burden;
- Regardless of the reference frame, the proposed controller can effectively deal with the periodic signals. This is unlike existing PI or PIR controllers in which the control systems have to be changed when using different reference frames.

The third contribution of the research work is the proposal of a novel configuration of DCMG-connected DFIG and the development of corresponding controllers for the elements in the DCMG.

A generic DCMG can be divided into different nodes and each node can consist of local sources and local loads. In order to keep the cost of DFIG at a low value, a novel configuration of DFIG interfaced with DCMG is designed in which the stator is connected to the DCMG using a SSR. In this configuration, the harmonic problem is analyzed. For the purpose of stator current harmonic elimination, the PIRC is applied in the control of RSC. And for the stator power harmonic control, a SC is installed at the DCMG and PIRC is applied in the control of SC to compensate the harmonics in the stator power.

Moreover, to achieve high efficiency in the DFIG, the DFIG is controlled for MPPT and a BESS is installed in each node to maintain the local voltage constant. This configuration not only improves the power efficiency of the DCMG, but also achieves a higher reliability of the system. When the BESS is fully charged/discharged or cut

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off due to faults, the DFIG will switch to another control model for the purpose of local voltage control. Furthermore, in order to achieve a stable DCMG voltage and equal load sharing, an improved droop control is applied in the DCMG voltage control.

1.5 Organization of the thesis

The organization of the thesis can be summarized as follows.

In Section 2.1, a brief literature review on LVRT of DFIG is given. The benefits and disadvantages of crowbar, ESS, injection voltage, on-load tap changer and decoupled protection methods are discussed in Sections 2.1.1, 2.1.2, 2.1.3, 2.1.4 and 2.1.5, respectively.

In Section 2.2, the literature review on harmonic control of DFIG is given. The method of installing an active power filter is analyzed in Section 2.2.2. The corresponding reference frames are introduced in Section 2.2.3 and 2.2.4 for harmonic elimination using PI and PIR type controllers, respectively. Finally, the PIRC technique is introduced in Section 2.2.5.

The literature review on DCMG is given in Section 2.3. The DCMG voltage controlled by a grid converter (GC) and a large synchronous generator is discussed in Section 2.3.1 and 2.3.2, respectively. A distributed voltage control by distributed sources is described in Section 2.3.3. The configuration of a DCMG-connected DFIG with a fully rated GSC is introduced in Section 2.3.4 and that with a stator-side converter (S-SC) is discussed in Section 2.3.5.

Based on the analysis in Section 2.1, an improved MSDFIG is proposed in Chapter 3. The basic concept of DF and IG mode of connection is introduced in Section 3.2 and the transient current analysis is shown in Section 3.3. The controller design for RSC, GSC and SSC is discussed in Section 3.4. The simulation and experimental results are given in Section 3.5 to verify that the MSDFIG can improve the LVRT performance of DFIG significantly.

In Chapter 4, the harmonic elimination of stand-alone DFIG is discussed. The modeling of stand-alone DFIG is given in Section 4.2 and based on that, the coordinated control method using PIRC is developed in Section 4.3. The system analysis is performed in Section 4.4 to guarantee the stability and effectiveness. Finally, the effectiveness of the proposed control has been proved by simulation and experimental results.

A novel configuration of DCMG-connected DFIG is proposed in Chapter 5. In the proposed configuration, an SSR is connected between the stator and the grid. The introduction of DCMG with distributed generators and loads are given in Section 5.2 and the aims of the controller design are discussed. The harmonic problem and the corresponding harmonic elimination control using PIRC are discussed in Section 5.3. In Section 5.4, the stator power harmonic elimination is achieved by installing an SC which is controlled using PIRC. The improved droop control for DCMG voltage and the reliability improvement by control mode selection are introduced in Section 5.5. Finally, the effectiveness of stator current harmonic control is verified by simulation and experimental results. The performance of stator power harmonic control and DCMG voltage control are illustrated in Section 5.6.

Chapter 2. Literature Review

2.1 Literature review on LVRT of DFIG

In this section, a brief literature review on LVRT of DFIGs will be given. The LVRT techniques such as crowbar, ESS, injection voltage, on-load tap changer and decoupled protection methods are discussed in detail. However, there are certain problems still need to be solved. For example, in all aforementioned LVRT techniques, the DFIG may absorb reactive power from the grid because the stator winding of DFIG is connected to the grid during fault. Such a scenario can deteriorate the fault condition. Moreover, when the grid voltage starts to oscillate in fault conditions, it can give rise to large transient stator and rotor currents if aforementioned LVRT methods are adopted. In order to overcome such drawbacks, the MSDFIG is proposed and discussed in Chapter 3.

2.1.1 *Review on crowbar protection*

The commonly used method for LVRT of DFIG is crowbar protection [36]. The topology for crowbar protection is shown in Figure 2-1. This topology is widely used in DFIG manufacturing because of its low cost. As described in [36], the controller of DFIG could be improved to help the DFIG ride through slight voltage drop or unbalanced voltage but for deep grid faults or the instances of DFIG working in high rotor speed conditions during grid faults could lead to large transient rotor currents. In such cases, the improvement of control strategy is not good enough for DFIG protection and thus a hardware protection is necessary. Most of the recent research is focused on this objective and the commonly accepted solution for this problem is to install a crowbar at the terminal of rotor winding. Many articles in literature have

Figure 2-1 Configuration of a DFIG wind turbine system with a crowbar system

researched on this topology of crowbar circuit recently. There are three aspects of crowbar circuit that have been researched.

- Resistance determination of crowbar protection design

The research on how to determine resistance of crowbar is introduced in [37] and [38] which insist that the resistance determination is quite important in crowbar protection system. If the resistance is too small then it is hard to reduce the rotor transient current rapidly and if it is too large, then the transient voltage that the converters have to suffer could be too high and as a result, the power electronic devices could be damaged. In DFIG design, the resistance of the crowbar is somewhat determined by experience.

- Control of crowbar connection

The most commonly used control strategy of crowbar connection is to detect the rotor current and if it is over current, the crowbar should be connected. In [39], the rotor current is also detected but a time delay is used in this control strategy for the purpose of avoiding too frequent connection and mal-operation of the crowbar.

Research in [40] proposed a voltage detecting method for crowbar control and if a voltage drop is detected then the crowbar circuit is connected and is disconnected after a time delay. Both the rotor current and grid voltage are detected in [3] and the crowbar should be connected to the rotor windings either when the voltage drop or current increase is detected.

- Control of crowbar disconnection

The crowbar circuit disconnection is more important compared with the connection because either too early or too late disconnection is harmful for the DFIG system. This is because after the rotor winding is connected with the crowbar, the DFIG would work like squirrel type generator which would absorb reactive power from the grid. When a grid fault occurs, if the generator absorbs reactive power from the grid, it cannot help the system recover from the fault condition and thus, long term connection of the crowbar should be avoided in DFIG operation. On the other hand, if the crowbar circuit is disconnected from the DFIG before the transient rotor current decreases to a certain value, the control system would connect the crowbar circuit to the rotor again. Thus, it is not good for the stability of the DFIG system.

Furthermore, after the crowbar circuit is connected, the determination of the reference value of the rotor current control loop and the design of the PI controller are very important. In [41], it is pointed out that if the reference value of rotor current is not given correctly, it could lead to the over current in rotor circuit again and re-connection of crowbar circuit. Actually, every part of a DFIG crowbar system needs to work cooperatively under a correct logical controller for successful LVRT. But unfortunately, no paper in the literature discusses about this subject until now and this is one of the main further works for LVRT of DFIG.

2.1.2 Review on ESS protection

Besides the crowbar protection of the DFIG, an ESS protection could be considered in LVRT of DFIG which is shown in Figure 2-2. In many cases, the dynamics of the DC-link voltage are ignored but it is also important to keep the DC voltage steady [42]. The energy stored in the ESS would change by controlling the ESS voltage. Therefore, the ESS could be used to absorb the power which could otherwise damage the converters. Another alternative way similar to ESS protection is to use a dumping resistance instead of the energy storage device. This circumvents the problems associated with transfer between the different operating modes. The drawback of this topology is that the rotor side converter must be sized accordingly. However, the gains associated with continuously controlling the machine throughout the fault may outweigh the cost of over-sizing the converters. Furthermore, the overrating will only be required for the current carrying capability of IGBTs. The thermal time constant is sufficiently long in order to handle dissipation of the additional energy. Numerous energy storage devices are researched in wind energy storage techniques [43-46], such as supercapacitor energy storage and fuel cell storage.

The alternate variable-speed WTG topology is that of the full converter interfaced machine, typically a synchronous machine with either wound rotor or permanent magnet. The advantages of this topology lie in the decoupling of the grid dynamics from those of the machine, achieved by the isolation resulting from the power electronic converter. For low voltage events, the energy that is produced by the machine still needs to be managed, particularly for severe, long duration events, which cannot be absorbed by the DC capacitor. For the DFIG, various alternatives exist.

Figure 2-2 Configuration of a DFIG wind power system with an ESS protection

Based on the same premise as in the previous section, an ESS can be used to manage the energy during a voltage disturbance. In this case, the energy is stored and subsequently, exported to the grid once the voltage returns to its nominal value. This capability may be useful during normal operation to achieve other beneficial characteristics. However, the transient rotor current which may damage the RSC during the grid fault conditions will not be reduced by controlling ESS. Therefore, the LVRT performance of DFIG by installing an ESS is limited. Note that this alternative requires a bidirectional converter, implying an additional IGBT [47].

2.1.3 Review on injection voltage protection

As the purpose of protecting the DFIG is to help the generator ride through low grid voltage and thus if a series injected voltage is added between the grid and the stator terminal of the DFIG, then the grid voltage drop could not influence the DFIG [48, 49]. For this reason, two topologies of voltage injection protection methods with series grid side converter are proposed in [50] for LVRT of DFIG. Figure 2-3 shows

the Y point connected series grid side converter topology and the transformer interfaced series grid side converter topology is shown in Figure 2-4.

Figure 2-3 Configuration of a DFIG wind power system with a Y point connected series compensation

Figure 2-4 Configuration of a DFIG wind power system with a series connected transformer compensation

- Y Point Connected Series Grid Side Converter

In the Y point connected configuration, the series grid side converter is connected to the open terminals of the DFIG's stator windings. The advantage of this scheme is that it allows the series grid side converter to directly modify the net voltage applied to the stator windings without using the injection transformer.

The series grid side converter is directly connected to the Y point of the DFIG, and shares the same current as the stator circuit. Nonetheless there is still sufficient flexibility to adjust the voltage and current ratings of the system to independently set the VA rating of the series grid side converter based on ride through requirements.

In conventional DFIG architectures the DC link voltage is selected based on efficiency considerations for the RSC and GSC. Along with the modulation strategy, the DC link voltage sets the maximum AC voltage of the series GSC. For a given power throughput the DFIG stator circuit, the stator current can be controlled by regulating the output voltage of the series connected grid side converter.

Therefore the nominal DFIG stator voltage is set by the ratio of series grid side converter AC voltage to nominal DFIG stator voltage which is necessary to achieve successful voltage sag ride through. The rotor circuit and grid side converter circuit can maintain their optimal voltage ratings by adjusting the rotor to stator turns ratio within the DFIG and the grid side converter transformer turns ratio on the farm collector transformer, respectively.

- Transformer Interfaced Series Grid Side Converter

In this configuration which is shown in Figure 2-4 the series grid side converter is connected via a three phase injection transformer in series with the main stator

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windings of the DFIG. The Y point of the machine is internally tied together as in a conventional DFIG.

The series grid side converter, three phase injection transformer and inductive filter all share the same current as the stator circuit of the DFIG referred to the series grid side converter side of the injection transformer. The three phase inductive choke filters the high frequency component of the converter voltage to limit harmonic losses in the injection transformer. The series grid side converter is assumed to operate infrequently and thus does not include a capacitor before the injection transformer. A relatively high switching frequency is assumed for the series grid side converter to mitigate transformer losses.

The use of the series transformer for voltage injection allows the ratio of the series grid side converter to nominal DFIG stator voltage to be set completely independently from the specific DFIG stator voltage. In this case, the voltage rating of the series grid side converter and the three phase injection transformer are determined by the injection voltage necessary to achieve satisfactory ride through.

2.1.4 Review on injection voltage protection Review on on-load tap changer protection

Figure 2-5 shows a simplified diagram of DFIG connection with an on load tap changer transformer. The transformer is connected to the point of common coupling (PCC) directly.

Figure 2-5 Configuration of a DFIG with an on load tap changer transformer

For the configuration of Figure 2-5, the control of the voltage at DFIG stator v_g or infinite bus v_{ig} can be done in several ways, in accordance with (2-1) or directly by changing the tap ratio of the on load tap changer transformer.

$$v_{ig} \approx v_g - \frac{R(P_g - P_L) + X(\pm Q_g - Q_L)}{v_g} \quad (2-$$

1)

Based on the formulae above, it could be found that the function of voltage control could be achieved by this configuration. Firstly, for slight grid voltage oscillations, the DFIG stator voltage could be controlled to be constant by changing the output active power and/or reactive power. And secondly for deep voltage drops, the on load tap changer transformer could work to increase the generator side voltage and by which the grid low voltage fault could be ridden through by DFIG.

For the cases described here it is assumed that the reactive power requirements of the system are met within the ratings of the wind farm equipment. Hence, the control of external power factor compensation is not considered. Control of the active power

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is documented in the published literature [51, 52]. However, active power control is not used by the proposed voltage controller. Within the system described here, active power control is assumed to be used for both the dispatch of active power and a frequency limiting function.

On load tap changer transformer are applied within several types of voltage control strategy used by transmission and distribution network operators and some methods have been compared. Whilst the referenced literature describes how the on load tap changer transformer can be used within a steady-state AC voltage control strategy, it may also be used to improve the dynamic range of the DFIG itself. The concept is a similar control technique to that used within HVDC schemes where the on load tap changer is used to ensure that the firing angle is controlled within a defined operating range for given AC system voltage. The control strategy utilizes a co-ordinated control of the on load tap changer and the generator reactive power.

2.1.5 Review on decoupled-DFIG

Figure 2-6 illustrates a decoupled-DFIG applied for LVRT [53]. A crowbar is applied in this topology and when a grid fault occurs, the DFIG could switch to induction machine mode with the grid-side converter becomes a STATCOM and the rotor-side converter is disabled. The crowbar effectively decouples the back-to-back converter unit from the DFIG, and enables the DFIG to operate as an induction generator (IG). Transition from a DFIG to an IG provides a mechanism to exploit the inertial response capacity as an IG.

Normally, the crowbar resistance is fixed. However, an optimal crowbar resistance can improve the active power performance during the fault period, while exploiting the inertial response capabilities during the post-fault period for this structure. The

DFIG works as an induction generator while the rotor speed is in super-synchronous region and an induction motor while the rotor speed is in sub-synchronous region in grid fault conditions. For this reason, the optimal crowbar resistance control is to minimize the active and reactive power consumed from the grid when the DFIG works in induction motor mode and in IG mode the crowbar resistance is controlled to maximize the active power generated as well as to improve the inertial response.

Figure 2-6 Decoupled-DFIG applied for LVRT

The benefits of decoupled-DFIG are that the converters could be protected during fault conditions and the grid-side converter acts as a STATCOM to compensate the reactive power. But the disadvantage is that the DFIG would work as an induction motor to consume active and reactive power from the grid which is not economical and even may be harmful for the grid voltage recovery.

2.2 Literature review on harmonic control of DFIGs

2.2.1 *Introduction*

Harmonic problems need to be addressed both in stand-alone DFIGs and grid-connected operation of DFIGs. In stand-alone DFIGs, when nonlinear or unbalanced loads are connected at the PCC, the voltage at PCC will be distorted by harmonic and unbalanced components. As a result, the quality of the power supplied to the other loads at the PCC will be degraded. What's more, the distorted stator voltage leads to harmonics in the stator current which is harmful for the generator. So for the purpose of a higher power quality, the harmonics of the voltage at PCC and of the stator current should be eliminated.

On the other hand, in grid-connected DFIGs, the grid voltage could be polluted by harmonics and unbalanced components as well. For example, as will be introduced in Chapter 5, when the DFIG is connected into a DCMG and an SSR is connected between the stator and the DCMG, the stator voltage would be distorted significantly. As a result, the armature current of the DFIG will contain harmonic components. Therefore, in grid connected DFIGs, the harmonics of stator currents should be eliminated when the grid voltage is distorted.

Some harmonic control methods have been proposed in previous literatures. The harmonic load current can be compensated by using a traditional PI controller, designed based on the synchronous reference frame [13]. Alleviation of the identical voltage quality problem using PI controller based harmonic reference frames have been proposed in [14]. Alternatively, PIR schemes have been proposed in [6, 16, 17, 54]. While the PIR of [16] is effective in reducing the 5th and 7th harmonic

components, two resonant loops are required for each order of the harmonic at the corresponding resonant frequency and thus increases the computational effort.

In this study, the frequency of the fundamental component of stator output voltage is to be maintained constant at 50Hz by controlling the slip frequency of the rotor current. Figure 2-7 is a vector diagram showing the fundamental component and harmonics both in different reference frames. One could find out that in this figure,

Figure 2-7 The vector diagram respecting the relationship between different reference frames

there is a stator stationary frame ($\alpha_s\beta_s$), a fundamental synchronous frame (dq^1) rotating with an angular speed ω_s . This figure also shows the harmonics frames in different sequences, negative fifth and eleventh harmonic frames (dq^5) and (dq^{11}) rotating with angular speed $-5\omega_s$ and $-11\omega_s$ respectively and positive seventh and thirteenth harmonic frames (dq^7) and (dq^{13}) rotating with angular speed $7\omega_s$ and $13\omega_s$ respectively are also included. Here a vector F stands for voltage, current and flux of the DFIG. As a result, the relationship of the vector F between stationary frame and harmonic frame could be expressed as

$$F_{dq}^5 = F_{\alpha_s\beta_s} e^{j5\omega_s t} \quad (2-2)$$

$$F_{dq}^7 = F_{\alpha_s \beta_s} e^{-j7\omega_s t} \quad (2-3)$$

The superscripts 5 and 7 means the fifth and seventh harmonic reference frames, respectively. Here we take 5th and 7th harmonic as an example for analysis and the 11th and 13th harmonic analysis is similar. (2-2)-(2-3) show that compared with the stator stationary reference frame, the 5th and 7th reference frame rotates with $-5\omega_s$ and $7\omega_s$, respectively. The RSC controller is based on the fundamental synchronous frame and thus, the vector F could also be expressed in the fundamental synchronous frame. The relationships and conversions between synchronous reference frame and different rotating reference frames are given.

$$F_{dq}^1 = F_{\alpha_s \beta_s} e^{-j\omega_s t} = F_{dq}^5 e^{-j6\omega_s t} = F_{dq}^7 e^{j6\omega_s t} \quad (2-4)$$

Accordingly, the vector with harmonics such as stator current could be expressed in the fundamental component reference frames, i.e., synchronous reference frame with their respective the fundamental and harmonic sequence components.

$$F_{dq}^1 = F_{dq,1}^1 + F_{dq,5}^1 + F_{dq,7}^1 = F_{dq,1}^1 + F_{dq,5}^5 e^{-j6\omega_s t} + F_{dq,7}^7 e^{j6\omega_s t} \quad (2-5)$$

In (2-5), the subscripts 1, 5 and 7 indicate the different order harmonic components. According to (2-5), one could find that different order harmonics in different rotating frames can be converted to DC values. Thus, it is possible to apply PI controllers to reduce harmonics.

2.2.2 Active power filter for harmonic elimination

Active power filter (APF) technique is a commonly used method for harmonic control [55]. The configuration of a stand-alone DFIG connected with an APF for

voltage compensation at PCC is shown in Figure 2-8. The voltage harmonics at the PCC can be compensated by controlling the APF output voltage.

Figure 2-8 PCC voltage harmonic elimination of stand-alone DFIG using APF

Figure 2-9 Stator current harmonic elimination of grid-connected DFIG using APF

Similarly, with the configuration of grid-connected DFIG shown in Figure 2-9, the stator current harmonics of the DFIG can be compensated by controlling the APF. Compared with the harmonic elimination methods discussed in the following sections, the APF technique is always easier to implement. But unfortunately, the benefits of

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APF technique are limited because one more converter is required to absorb the harmonics. As a result, the cost of the system will be significantly increased. On the other hand, the harmonic elimination by controlling RSC has become a potential way forward. Thus, APF technique will not be considered for harmonic control unless necessary.

2.2.3 PI controller for harmonic elimination

Based on the analysis in Section 2.2.1, in order to eliminate the harmonics in stator current, one proposed control scheme is to produce a proper rotor current to compensate the non-sinusoidal stator current and thus reduce the harmonics [14]. In order to get a better performance in harmonic compensation, the 11th and 13th harmonic components are considered. Thus, to achieve this function, the 5th, 7th, 11th and 13th sequence harmonics of the stator current should be detected. Assume the stator voltage and current are balanced. Thus, firstly, two current sensors are used to detect the stator current. And eight band-pass filters are needed to extract the harmonics from the current signals. After that, the harmonics in different orders are transferred to the corresponding reference frames rotating with angular speed $-5\omega_s$, $7\omega_s$, $-11\omega_s$ and $13\omega_s$ to get the dc value i_{sdq5}^5 , i_{sdq7}^7 , i_{sdq11}^{11} and i_{sdq13}^{13} , respectively. Finally, to eliminate these harmonics, four PI controllers are applied to generate reference harmonic sequence components of rotor voltage. The input of the PI controller is the dc current harmonic error compared with zero. This controller could generate the rotor current tracking the reference value and thus, a corresponding proper stator current could be achieved and the harmonics can be reduced. The proposed control scheme is shown in Figure 2-10.

Figure 2-10 Control scheme of the grid connected DFIG for stator current harmonic elimination using PI controller

It could be found that with the traditional PI controller, the methods require large amount of calculations because the elimination of the unbalanced or a given order harmonic component each requires a BPF, a dq -frame followed by a reversed dq -frame transformation between the corresponding rotating frequencies. What's more, the negative sequence component control loop should be included into the controller in order to mitigate the unbalanced component.

2.2.4 PIR controller for harmonic elimination

An alternative method for harmonic control is using PIR technique [6, 16, 17, 54]. In stand-alone DFIG, in order to reduce the harmonics in stator voltage, the proposed controller using PIR technique in synchronous reference frame is shown in Figure 2-11.

Figure 2-11 Control scheme of stand-alone DFIG using PIR in synchronous frame

Similar to the control scheme of the grid connected DFIG for stator current harmonic elimination, the control scheme of stand-alone DFIG using PIR control requires BPFs to detect the 5th and 7th order of harmonics. After the harmonic components are transferred into their corresponding reference frames, PI controller could be applied to calculate the reference rotor current for harmonic compensation. The reference current should be transferred into reference frame in which the reference rotor current will contain periodical signals. Thus, in order to track the reference rotor current, resonant loop should be included into the controller to regulate the periodical components.

This PIR controller could also be applied in stationary reference frame for stator voltage harmonic elimination of stand-alone DFIG as shown in Figure 2-12. This method is similar to the control scheme of stand-alone DFIG using PIR in synchronous frame. But in stationary reference frame, the reference rotor current contains periodical signals fundamental component, 5th and 7th harmonic

proposed resonant control loop could be applied for harmonic compensation. The 6th order harmonic resonant control transfer function is given by

$$G_R = \frac{2k_r\omega_c s}{s^2 + 2\omega_c s + (\pm 6\omega_s)^2} \quad (2-7)$$

In (2-7), k_r is the resonant control gain and ω_c is the cut-off frequency which determines width of the resonant peak. In the synchronous reference frame, if the 6th order harmonic resonant controller could achieve nearly zero steady-state error, the 5th and 7th order harmonics in the stator current could be eliminated if the commanded value is set to zero. The proposed control scheme for stator current harmonic elimination of grid-connected DFIG is shown in Figure 2-13.

Figure 2-13 Block diagram of stator current controller

The schematic representation of current control loop of the DFIG is shown in Figure 2-14. In the fundamental reference frame, the fundamental components become DC quantities and the 5th and 7th order harmonic components become AC quantities with the sixth multiple of synchronous frequency. The resonant compensator is capable of sufficiently tracking the AC reference current and it can

eliminate the steady-state control variable errors at the resonant frequency. According to Figure 2-13, the closed-loop transfer function of stator current is determined as

$$i_{s,dq}(s) = G_1 i_{s,dq}^*(s) + G_2 i_{r,dq}^*(s) + G_3 v_{s,dq}(s) \quad (2-8)$$

Figure 2-14 Improved control scheme of the grid-connected DFIG using resonant loop

where G_1 , G_2 and G_3 are the transfer functions from commanded stator current, commanded rotor current and stator voltage to actual stator current respectively.

According to Figure 2-13, these transfer functions could be expressed as

$$G_1 = \frac{i_{s,dq}(s)}{i_{s,dq}^*(s)} = \frac{2L_m k_r \omega_c s^2}{N(s)} \quad (2-9)$$

$$G_2 = \frac{i_{s,dq}(s)}{i_{r,dq}^*(s)} = \frac{L_m (s^2 + 2\omega_c s + 36\omega_s^2) (k_p s + k_i)}{N(s)} \quad (2-10)$$

10)

The analysis above all concern about the harmonic elimination control. For the purpose of negative sequence component elimination in unbalanced load conditions, some adjustments have to be made in PIR controllers. The proposed control scheme for stator voltage unbalanced component elimination is shown in Figure 2-16. In Figure 2-16, G_{Ru} is the resonant loop regulating the negative sequence component. In this control scheme, the stator voltage is converted into synchronous reference frame in which the negative sequence component is with rotating speeds of $-2\omega_s$. The transfer function of G_{Ru} can be expressed as

Figure 2-16 Improved control scheme of the DFIG using PIR for unbalanced component elimination

$$G_{Ru} = \frac{k_{ru}s}{s^2 + (-2\omega_s)^2} \quad (2-13)$$

As could be found according to the analysis above, the PIR technique can be used for harmonic elimination of DFIG. Compared to the PI controller introduced in Section 2.2.3, PIR control can deal with periodic components so that the calculation

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can be simplified. For PIR techniques, it is important to choose a proper reference frame and the controller design is strictly based on the frequencies of the harmonic components in that reference frame. Harmonics in different orders have to be dealt with separately. For the purpose of unbalanced component elimination, one more resonant loop for negative sequence component control is required. Consequently, the main drawback of PIR controller is that each resonant loop can only damp the harmonic component corresponding to its resonant frequency.

2.2.5 PIRC controller for harmonic elimination

RC technique for periodic signal control is researched extensively recently [21, 57, 58]. Periodic signals of period T can be generated by the system shown in Figure 2-17(a) while the basic RC loop is shown in Figure 2-17(b), where k_{rc} is the gain of the loop, $G_f(s)$ is a phase lead compensator and Q is a low-pass filter which could be set to be constant [19]. $I_{RC}(s)$ and $O_{RC}(s)$ are the input and output signals of the RC loop, respectively. Thus, the transfer function of RC loop is

$$G_{RC}(s) = \frac{O_{RC}(s)}{I_{RC}(s)} = \frac{k_{rc} G_f(s) Q e^{-sT}}{1 - Q e^{-sT}} \quad (2-14)$$

In general, zero steady-state error tracking of an external periodic input can be achieved by incorporating the RC scheme into a closed-loop system [59].

A hybrid control scheme with traditional PI controller and RC for the purpose of harmonic compensation of a grid-connected inverter is introduced in [19]. The control

scheme for harmonic elimination in synchronous frame of the inverter is shown in Figure 2-18. In this control scheme, the fundamental component is usually controlled for DC voltage regulation which is not our concern in this section. The harmonic component is controlled in synchronous frame in which the 5th and 7th harmonics are with rotating speeds of $-6\omega_s$ and $6\omega_s$, respectively. But according to the bode diagram of PIRC, the controller can damp periodic components with rotating speed of integral multiples of fundamental frequency. With this in mind, it is noticed that regardless of the reference frame, the PIRC could be used for harmonic elimination control. For the harmonic elimination of the inverter shown in Figure 2-18, the control scheme of PIRC in stationary reference frame is shown in Figure 2-19.

Figure 2-18 Three-phase grid-connected inverter with hybrid PIRC control scheme in synchronous frame

In stationary frame, the fundamental component rotates with fundamental frequency and the 5th and 7th harmonic components rotating with frequencies as 5 and 7 multiples the fundamental frequency so that RC loop can be applied for both fundamental and harmonic components control. Thus, compared with the PI and PIR control for harmonic elimination, PIRC is simpler and with less calculation burden.

Figure 2-19 Three-phase grid-connected inverter with hybrid PIRC control scheme in stationary frame

The PIRC technique will be developed in Chapter 4 for stator voltage harmonic elimination of stand-alone DFIG and in Chapter 5 for stator current and power harmonic control of DCMG-connected DFIG.

2.3 Literature review on DC-microgrids

DGs systems are increasingly researched and installed in utility grid in the present time [24-28]. However, high penetration of DGs would lead to problems like voltage variations and protection issues. Thus, MGs are researched extensively in order to solve such problems. The conventional electrical systems today are powered by AC mains. But as renewable technologies such as solar photovoltaics and wind power become more prevalent, DC microgrids (DCMGs) can become economical and more efficient alternative. DCMGs consist of power generators such as PV, wind and fuel cell, electrical storage devices such as super capacitors and batteries and loads. DCMGs can be built up in small-scale residential, remote/sparsely populated areas or

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commercial/data centers. Nowadays, many renewable sources generate DC, such as photovoltaic, wind and fuel cells. Compared to grids, when supplied with DC sources the conversion efficiency of DCMGs is higher. Moreover, DC power can be easily stored in batteries. As a result, it is predicted that DCMG will be applied increasingly in the future [30].

A typical DCMG consists of distributed nodes. Each node can be comprised of sources, energy storage devices and loads. Different nodes are connected by distribution lines. Each node in the DCMG can be regarded as a unit which delivers or absorbs power from the DCMG.

The power management of DCMG is greatly discussed in the previous literatures. The power flow will be determined by the voltage distribution in the DCMG. A common voltage control method has been proposed in [64-68] using grid converters (GCs). In this method, the excess power from the distributed generators or load demand will be absorbed or met by GC. As an alternative method, a large source like a synchronous generator with a large capacity to support the voltage is proposed. More recently, the voltage control by distributed sources is proposed in isolated DCMGs. This method can improve the power flow control but the control of the distributed generators need communications.

Importantly, it is described in Section 1.1 that DFIG is more attractive from an economical point of view because the power converter of the DFIG only handle 20% to 30% of the total power. However, there are many problems associated with DFIG interfaced AC power systems. For example, with the integration of large-scale wind farms, the operating frequency of power grid will be impacted due to the lack of frequency regulation support from wind turbines which is caused by the decoupling control system in DFIGs [60, 61]. Therefore, a significant number of recent research

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works have proposed that DFIGs can be connected to DCMGs to overcome the frequency regulation problem. Moreover, the LVRT problems associated with DFIGs discussed in Section 2.1 will no longer exist because the DCMG doesn't require reactive power.

When the DFIG is connected to the DCMG, a new scheme is needed to convert the AC power from DFIG to DC power to be consumed by the loads on DCMG. Although certain previous research work have proposed some new configurations of DFIG interface to DCMGs, unfortunately, DFIGs will lose their benefits in some of the proposed configurations. A novel configuration will be discussed in Chapter 5 and the harmonic problem in the new configuration will be solved using PIRC introduced in Section 2.2.

In order to achieve a better stability of the system, equitable load sharing and stable DC voltage at each node is required. Moreover, it is also necessary to deal with the condition that arises when the sources are cut off in some nodes. In such a condition, it is required that the DC voltage at each node needs to be kept stable and the load sharing should be adjusted.

2.3.1 DCMG voltage controlled by GC

In DCMGs, the DC voltage regulation is a key concern. Voltage control methods have been discussed by many researchers. In grid-connected DCMG shown in Figure 2-20, it is proposed that the voltage is controlled by a GC.

Figure 2-20 DCMG with the voltage controlled by GC

In the proposed controller, the DC voltage is maintained by regulating the output current of GC [62-66]. In this configuration, the control for the sources can be designed for MPPT to achieve a high efficiency. The excess power will be delivered to the AC grid through GC when the power generated by the sources is larger than the load demand. However, and on the other hand, when the load demand is higher than the supplied power, the insufficient power will be supplied by GC. But this configuration would not be available in some rural areas or islands where it could be difficult to interface such power systems with a large grid. Even in AC grid connected DCMGs, this method needs to be further developed because the DCMG has to be isolated from the large AC grid when a fault occurs. Furthermore, the voltage of each node in the DCMG varies because of the resistance and reactance of the distribution line. Especially when there is a heavy load in the DCMG, the large load current can cause a significant voltage drop on the distribution line and the voltage oscillation will make the DCMG voltage unstable.

Figure 2-21 DCMG with its voltage controlled by CSG

2.3.2 DCMG voltage controlled by a large source

As shown in Figure 2-21, an alternative configuration for the DCMG is proposed in [34]. A synchronous generator is installed in the DCMG and the DC voltage is maintained by control of converter of synchronous generator (CSG). The d-axis of generator current is regulated for DCMG voltage control and the q-axis is for reactive power control of the synchronous generator. The generator will stop providing active power to the DCMG when the power generation in the DCMG is greater than the load demand. The energy storage system in the DCMG will absorb the excess power. The synchronous generator will generate power to the DCMG when there is no sufficient power generation from existing sources for the load demand.

This configuration can solve the problem that in some rural areas or islands where it is hard to interconnect the power system with a large grid while the other sources in the DCMG can be controlled for MPPT to achieve a high efficiency. But this

configuration requires a synchronous generator with a large capacity to support the grid. It makes the cost of the system significantly high to operate the DCMG in such a configuration. Furthermore, similar to the grid-connected DCMG, the voltage stability cannot be guaranteed. The operating point of the synchronous generator changes with the mismatch between the power generation and load demand. Alternatively, a large capacity energy storage can be installed in place of the synchronous generator to handle the mismatch between the supply and demand. However, the cost of energy storage will increase with its power rating significantly. Therefore, it is necessary to improve the control scheme of the distributed sources as an effective way to avoid the frequent change of synchronous generator operating point or as an alternative for the use of large capacity energy storage. The proposed control scheme of the distributed sources will be discussed in Chapter 5 in great detail.

2.3.3 DCMG voltage controlled by distributed source

Figure 2-22 Configuration of a DCMG-connected DFIG with individual voltage control

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More attractive control method for DCMG voltage control by distributed sources has been reported in [69]. As shown in Figure 2-22, sources and storage elements are controlled to supply high reliability power to loads. The DCMG voltage control method by distributed sources can be used when the DCMG either in isolated or AC grid connected mode. A traditional voltage control method for the distributed sources is to reduce the power loss in the distribution line as much as possible. In this method, the voltage at each node of the DCMG will be controlled with a same reference value so that the current flow through the distribution line will be reduced. This method reduces the power loss but unfortunately, the mismatch between the power generation and load demand will affect the performance badly. For example, in the DCMG, in some nodes the load demand can be smaller than the power generation and some nodes otherwise. In such nodes the load demand is lower than the power generation, an ESS with a large capacity should be used to absorb the excess power in the node. Otherwise, the power generation of the local source has to be reduced. Conversely, if the load demand is larger than the power generation, the ESS should supply power to meet the demand but when the ESS is fully discharged, some loads have to be shed to reduce the burden of the sources. But if an equitable load sharing is applied, the excess power in some nodes can be delivered to those nodes where there is shortage of power.

In this configuration of DCMG, droop control can be applied in the DCMG voltage regulation and thus, the voltage can be kept more stable and the reliability of the DCMG can be improved. However, the control of DCMG without communication as shown in Figure 2-22 will lead to an unequal load sharing due to error in normal voltages or load distribution in DCMG. Thus, the configuration and control scheme of such system need to be improved.

Moreover, in DCMGs, renewable energy plays an important part in the power supply. If renewable energy sources are used for voltage regulation, it will lose the MPPT control and the efficiency of the sources will be reduced. Also, as such sources are intermittent in nature, voltage regulation may not become possible at certain source conditions. As a result, ESS needs to be installed into the nodes and used for voltage control. In such a scenario, renewable energy sources can be used to achieve MPPT. Therefore, a novel configuration of DCMG which consists of sources of BESS and DFIGs is proposed along with improved droop control and it is discussed in detail in Chapter 5. In order to improve the efficiency, the DFIGs are controlled for MPPT. And for the purpose of equal load sharing and stable DC voltage, the DCMG voltage is regulated by BESS using improved droop control.

2.3.4 DCMG-connected DFIG with a fully rated converter

The configuration of the DCMG-connected DFIG is another concern in this research. A configuration of DCMG-connected DFIG is proposed in [63] whence the AC power of the DFIG is delivered to the DCMG by a GSC. As shown in Figure 2-23, the GSC controls the stator voltage of the DFIG so that the AC power of the generator can be delivered to the DCMG. The power generated by the DFIG will be delivered to the DCMG through a GSC and the power rating of GSC is higher than the rated power of the DFIG.

Figure 2-23 Configuration of a DCMG- connected DFIG with a fully rated GSC

Similar to the conventional DFIG, in this configuration of DFIG, the LSC is used to maintain the DC-link voltage V_{DC} of the DFIG and the RSC is controlled for MPPT. This configuration of DFIG obtains the advantages that the stator voltage can be purely sinusoidal and the control of both the LSC and RSC can be kept as that of conventional DFIG.

However, the GSC should be at least fully rated to allow the rated power flow of the generator. It also increases the power loss with the use of an additional GSC so that the efficiency of the DFIG system is reduced. As a result, this configuration of DFIG loses the advantages from economical point of view in comparison to the conventional DFIG and it needs to be improved.

2.3.5 DCMG-connected DFIG with a stator-side converter

An alternative configuration which consists of an RSC and stator-side converter (S-SC) of DCMG-connected DFIG is shown in Figure 2-24. An S-SC is installed between the stator and DCMG to control the stator voltage. In this configuration, the RSC is controlled for the purpose of MPPT as usual.

Figure 2-24 Configuration of a DCMG-connected DFIG with a stator-side converter (S-SC)

Compared with the DCMG-connected DFIG with fully rated GSC, this improved configuration of DFIG could have a lower cost because it saves one converter. However, the co-operation of the S-SC and RSC is required which makes the controller to be increasingly complex. Furthermore, the S-SC should be fully rated because the stator power flow through S-SC could be as high as the rated power of DFIG. This disadvantage makes this configuration of DFIG to be costly that it requires further improvement

Based on this configuration, an improved configuration of DFIG has been proposed in [34]. In [34], the S-SC is replaced by an SSR. It keeps the cost of DFIG to a low value. However, it introduces some power quality problems. The uncontrollable SSR will lead to a distorted stator voltage and armature current. Therefore, the distortion has to be compensated which will be discussed in detail in Chapter 5.

Chapter 3. Design of Mode Switching Scheme for Low Voltage Ride Though of DFIG

In this chapter, a mode switching technique is proposed for grid connected DFIGs. In this technique, the DFIG is to switch from the conventional DF connection to the IG connection or vice versa, depending on the status of the DFIG terminal voltage. When a grid fault occurs and the DFIG terminal voltage is depressed, the DFIG is to operate in the IG mode. The stator windings are disconnected from the grid and the winding terminals are subsequently short circuited. This is done because the rotor transient current has an almost linear relationship with the stator current when the fault occurs. Thus by changing to the IG connection, the rotor current would be unaffected by the grid voltage because the stator is isolated from the grid. The desirable feature of this scheme over the other LVRT methods is that the generator remains connected to the grid through the rotor circuit.

Hence, compared to the commonly used LVRT technique introduced in [8, 53], the advantages of MSDFIG can be summarized as follows [34].

Generator control: Because of the RSC is disconnected from the DFIG when fault occurs, the commonly used LVRT technique loses the control of the generator during LVRT which is dangerous for the generator especially in high rotor speed conditions. On the other hand, MSDFIG is still under control even in grid fault conditions.

Reactive power control: The GSC is controlled within the power rating of the converter for reactive power control. The MSDFIG can achieve this aim too. However, the MSDFIG takes the advantage that the reactive power that is delivered to the grid

can be much larger than that of the method introduced in [53] because the uncontrolled generator in [53] may absorb large amount of reactive power in grid fault conditions [13].

Generator isolation: In the previous LVRT techniques like in [53], the stator of the generator is connected to the grid directly without protection and the generator is out of control. The possible voltage oscillation of the grid during grid fault conditions may be harmful for the generator. In MSDFIG, this negative effect can be avoided due to the isolation of the generator from the grid. The real power can also be generated and delivered to the grid in grid fault condition which is also a creative feature of MSDFIG compared to the other techniques.

Figure 3-1 Schematic of a grid-connected DFIG

3.1 DF and IG modes: basic circuit models

The schematic of a grid-connected DFIG is shown in Figure 3-1. The prime mover is a wind turbine controlled to generate the maximum mechanical power in accordance to the wind speed. The induction generator converts the mechanical power to electrical form which is then delivered to the grid through both the stator and the rotor windings. Figure 3-1 shows a transmission line-transformer electrical link interconnecting the DFIG to a large grid. This rather generic network can be used to

describe the impacts of a grid fault on the DFIG. When a three-phase-ground fault occurs within the grid system, the DFIG has to ride through the low voltage seen at the PCC. The PCC voltage would recover following the opening of the appropriate CB. Hence, the design of the MSDFIG must be such that under the IG mode, the large transient rotor current and slip power are controlled to acceptable levels. Furthermore, the MSDFIG is to ride through smoothly the voltage perturbations due to the fault, and the subsequent opening and possible reclosing of CB.

Figure 3-2 DFIG under (a) DF mode and (b) IG mode of connection

The conventional DF and the particular IG modes of connection are shown in Figure 3-2. Thus in the conventional DF mode, the sum of the stator power P_s and the rotor power P_r constitutes the output power P_d of the DFIG, if converter losses are ignored. While there are excellent works describing the DF mode of operation, the IG mode of operation of the wind generator is less well researched. Under the IG mode, the stator windings are disconnected from the grid and the windings are short circuited. A significant benefit of switching to the IG mode when the low-voltage incident occurs is that the large transient rotor current and the slip power transients caused by the voltage oscillations can be controlled to acceptable levels: the DC link voltage and

Figure 3-3 Equivalent circuit of the DFIG

the injected reactive power into grid are controlled by the GSC while the active power flow is controlled by the RSC.

The per-phase equivalent circuit model necessary for analyzing of the behavior of the generator under the DF and IG modes is given in Figure 3-3. v_s and v_r are the stator-side and rotor-side voltages of the DFIG respectively. In conventional DF mode of connection, v_s is at the nominal value of 1 p.u. but under IG mode, v_s can reach 0 p.u. if no external crowbar is connected to the stator and the stator side is short circuited, i.e. $R_{CB}=0$ in Figure 3-2(b). The dynamic behavior of the DFIG under the synchronous rotating reference coordinate is described by the following Park's equations:

$$v_{s,dq} = R_s i_{s,dq} + \frac{d\lambda_{s,dq}}{dt} + j\omega_s \lambda_{s,dq} \quad (3-1)$$

$$v_{r,dq} = R_r i_{r,dq} + \frac{d\lambda_{r,dq}}{dt} + j(\omega_s - \omega_r) \lambda_{r,dq} \quad (3-2)$$

2)

where

$$\left. \begin{aligned} \lambda_{s,dq} &= L_s i_{s,dq} + L_m i_{r,dq} \\ \lambda_{r,dq} &= L_r i_{r,dq} + L_m i_{s,dq} \end{aligned} \right\} \quad (3-3)$$

In these equations, $i_{s,dq}$ and $i_{r,dq}$ are the respective stator and rotor currents in the d-q reference frame. R_s , L_s , R_r and L_r are the stator and rotor resistances and inductances respectively. L_m is the generator magnetizing inductance. ω_s and ω_r are the stator-side frequency and rotor speeds. Equations (3-1) – (3-3) allow the behavior of the wind generator to be studied, as follows.

3.2 Analysis of transient current

From (3-1) – (3-3), it can be readily shown that the voltage equations for an induction generator in synchronous reference frame are given by

$$\begin{cases} v_s(t) = \left(R_s + j\omega_s L_s + L_s \frac{d}{dt} \right) i_{s,dq}(t) + \left(j\omega_s L_m + L_m \frac{d}{dt} \right) i_{r,dq}(t) \\ v_r(t) = \left[R_r + j(\omega_s - \omega_r) L_r + L_r \frac{d}{dt} \right] i_{r,dq}(t) + \left[j(\omega_s - \omega_r) L_m + L_m \frac{d}{dt} \right] i_{s,dq}(t) \end{cases} \quad (3-4)$$

As the converters must be protected against rotor circuit over-load, the following analysis is carried out in order to quantify the magnitude of the rotor transient current which will in turn lead to a proposed technique to limit the current.

3.2.1 DF to IG Mode Switch

When the induction generator switches from the DF to IG modes, the stator terminals are connected to a crowbar in the present scheme. In the following derivation and without any loss of generality, the crowbar resistance is merged into the stator winding resistance to yield the total stator resistance R_s . Furthermore, in order to simplify analysis, it is assumed that within the very short time when the generator switches from the DF to IG modes of operation, v_r and ω_r are constant. Hence, v_s changes from 1 p.u. to zero when the generator switches from the DF to the IG mode. Apply Laplace transformation to (3-4), the voltage equations become

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$$\left. \begin{aligned} -\frac{1}{p} &= (R_s + L_s p + j\omega_s L_s) i_{s,dq} + (L_m p + j\omega_s L_m) i_{r,dq} \\ \frac{v_r}{p} &= [R_r + L_r p + j(\omega_s - \omega_r) L_r] i_{r,dq} + [L_m p + j(\omega_s - \omega_r) L_m] i_{s,dq} \end{aligned} \right\} \quad (3-5)$$

where p is the Laplace operator.

The transient rotor current can be shown to be of the form

$$i_{r,dq} = C_0 + C_1 e^{\xi_1 t} + C_2 e^{\xi_2 t} \quad (3-6)$$

where the parameters ξ_1 , ξ_2 , C_0 , C_1 and C_2 can be determined using (A-3) and (A-4) shown in Appendix 3-A.

3.2.2 Technique to Limit the Transient Current

The results of the above analysis show a possible way to limit the rotor transient current is through the use of SSC which is represented by R_{CB} as shown in Figure 3-4. The SSC is used to limit the rotor inrush current. Unlike the use of rotor-side crowbar in the conventional design, the DFIG can still be controlled using the SSC.

In the design of the MSDFIG, the stator crowbar will only be activated by closing switch S_3 when the generator switches from the DF to IG modes. The crowbar limits the transient rotor current by dissipating the real power appearing in the transients. Subsequently the stator shall be disconnected from the grid through the opening of the switch S_1 and the resistance of the crowbar R_{CB} shown in Figure 3-2(b) in the stator circuit will be continuously reduced as the generator progresses toward a steady state in the IG mode. The reduction in resistance is achieved by controlling the duty-ratio D of the IGBT T_1 shown in Figure 3-4. Thus, the equivalent resistance of R_{CB} can be expressed as

$$R_{CB} = \frac{R_{syn} R_{CB1}}{R_{syn} + R_{CB1}} * (1 - D) \quad (3-7)$$

During the re-synchronization stage of the generator however, R_{CB} has to be of much higher value. So the relatively lower resistance (R_{CB1}) will be disconnected from the stator circuit through the opening of the switch S_2 . Effectively, the synchronization resistor (R_{syn}) shown in Figure 3-4 shall be inserted. Thus, the switches S_1 , S_2 and S_3 are envisaged to be electric-mechanical, power electronic and electric-mechanical switches, respectively.

MSDFIG under the synchronization mode will be discussed in greater details in Section 3-4.

Figure 3-4 DFIG with a stator-side crowbar (SSC)

3.3 Controllers design

The controllers for the MSDFIG operate under three possible scenarios. Under normal grid conditions, the DFIG is controlled to maximize energy harness from the wind. Under grid-fault condition however, the stator crowbar circuit is activated and

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the DFIG switches to the IG mode of connection during which the active power flow through the converters is controlled to within the power ratings of the converters. Following grid-fault clearance, the DFIG switches to the re-synchronization mode for which the amplitude, frequency and phase of the stator-side voltage vector $\overline{v_s}$ is controlled in synchronous reference frame to track the grid-side voltage vector $\overline{v_g}$. When $\overline{v_s} = \overline{v_g}$, S_1 shown on Figure 3-4 shall close and S_2 and S_3 open. Thus, the DFIG will revert back to the DF mode and normal operation resumes.

3.3.1 Controller for the GSC

The GSC controller is similar to that shown in [67]. Under normal conditions, the GSC is controlled to maintain the DC-link voltage through the manipulation of the d-axis current I_d and to ensure active power generated by the generator is fed to the grid. Under the IG mode and through the control of the q-axis rotor current, the GSC also controls the reactive power flow to the grid. Reference [67] provides a good discussion on the reactive power requirements. MSDFIG can generate and deliver reactive power to the grid and stays well within the power rating of the GSC when the grid fault occurs, based on the same reactive power control method as used in several LVRT techniques [5]. However, the proposed MSDFIG has distinct advantages over these conventional techniques, as shall be shown below.

3.3.2 Controller for the RSC

The schematic diagram of the control system for the RSC is shown in Figure 3-5. The stator and grid voltage are measured to decide the mode of the controller. In normal condition, the controller is in mode 1 (DF mode). When the stator and grid voltage is less than a lower limit of (say) 0.9 p.u., the controller will be switched to

mode 0 (IG mode). If it is detected that the grid voltage recovers, the controller will be switched to mode 2 (synchronization mode). After the synchronization is achieved the controller will be switched to mode 1. Under DF or mode 1, MPPT applies for real and reactive power control to achieve unity power factor. Under IG or mode 0, the rotor-side real power is regulated. The control system is designed so that the reactive power required to the grid shall be met while the rotor-side real power is controlled to ensure the apparent power delivered to the grid is within the rating of the GSC. In the synchronization or mode 2, the stator voltage is controlled for smooth and quick reconnection to the grid.

Figure 3-5 Control schematic for rotor-side converter

The RSC is controlled by a vector controller in the stator reference frame. Under the IG mode, the DFIG can still be controlled to generate real power during fault and this

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is a distinct advantage over other proposed schemes. The d-axis rotor current is controlled to regulate the active power flow through the converters.

By applying the equivalent circuit shown in Figure 3-3, one obtains

$$P_m = \frac{1-s}{s} \left(|i_r|^2 R_r + \text{Re} \{ v_r \bar{i}_r \} \right) \quad (3-8)$$

where P_m is the input mechanical power and s is the slip value. The rotor real power flow P_r and rotor losses $P_{r,loss}$ are given by

$$P_r = \text{Re} \{ v_r \bar{i}_r \} \quad (3-9)$$

$$P_{r,loss} = |i_r|^2 R_r \quad (3-10)$$

The relationship between the input mechanical power and output rotor power can be derived as

$$P_r = \frac{s}{1-s} P_m - P_{r,loss} \quad (3-11)$$

where $s = (\omega_s - \omega_r) / \omega_s$. Based on the power flow directional convention shown in Figure 3-3, the mechanical power P_m is negative while the rotor power P_r is positive under the IG mode. Whence

$$-1 < \frac{s}{1-s} \leq 0 \quad (3-12)$$

That is, the slip s must be negative. In the IG mode, it is desirable to increase the ratio P_r / P_s such that the power loss in the stator circuit would be minimized as in

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this way, the stator current can be reduced. Hence, s should be much less than zero and the DFIG needs to work in the highly super-synchronous region. To achieve the super-synchronous operation, one can either increase the rotor speed or decrease the stator frequency. Increasing rotor speed is not an acceptable option because of the large response time caused by the rotor inertia, as well as the upper limit placed on the rotor speed due to mechanical considerations. So the decrease of the stator frequency becomes the only way to increase the rotor output power. Given that the active power flow through the converters has to be below the power rating of the converters, the reference stator frequency $\omega_{s,fault}^*$ can be determined, as described below.

In IG mode, the machine becomes an inverter-fed induction generator. The equivalent circuit of the generator rotor reference frame is shown in Figure 3-6 where $a = (\omega_2 - \omega_r) / \omega_2$ and ω_2 is the frequency of the input voltage of the RSC. If the rotor losses are ignored, then the power delivered to the rotor-side converter equals to air-gap power, i.e. $P_r = P_g$. The air-gap power of the generator can be shown to be

$$P_g = \frac{3R_s i_s^2}{a} = 3v_r^2 \frac{R_s / a}{(R_s / a)^2 + (L_s \omega_2)^2} \quad (3-13)$$

To keep P_r under the power ratings of the converters, the rotor-side frequency ω_2 could be determined under different rotor speed conditions. Thus, a look-up table of ω_2 under different rotor speed ω_r conditions can be constructed so that under the IG mode, ω_2 can be readily determined once ω_r is known. Thus one can safely set the slip to be fixed in the operation region of the DFIG to keep P_r within the power ratings of the converters.

Figure 3-6 Equivalent circuit of the DFIG in the IG mode

- **Synchronization Control**

After fault clearance and voltage recovery is detected, the generator is to recover from the IG to the DF modes of operation. As shown in [12], direct reconnection of the stator to the grid could lead to large and persistent oscillations in P_d . The problem can be obviated by synchronizing $\bar{v}_s$ with $\bar{v}_g$ before s_1 is reclosed. Indeed, several methods have been reported in the literature concerning grid synchronization of DFIG. See e.g. [68]. Unfortunately the control strategies tend to be rather complex. Instead, the much simpler PI controller shown in Figure 3-5 is used in this thesis to show that it can perform sufficiently well for the problem in hand. To achieve the synchronization, it is required to track the grid voltage space phasor. Therefore, the grid voltage oriented reference frame shall be specified for the design of the synchronization controller. The d-axis of the synchronous reference frame is aligned to the grid voltage, i.e.

$$\left. \begin{aligned} v_{g,d} &= |v_g| \\ v_{g,q} &= 0 \end{aligned} \right\} \quad (3-14)$$

The stator windings are open-circuited when the DFIG is in grid synchronization mode. However, when the generator is switched from the IG mode to grid

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synchronization mode, the stator windings are switched from short circuit to open circuit. The stator current would be reduced to zero in the transient process. Special precaution has to be taken because the sudden current reduction would lead to a large voltage across the stator inductance. Thus, under the synchronization mode, S_2 is open, S_3 is still closed and T_1 is open. The resistance of stator crowbar shall be

$$R_{CB} = R_{syn} \quad (3-15)$$

The synchronization crowbar has a large resistance value to maintain the stator voltage in the synchronization mode.

Prior to the synchronization, one can assume a very low stator current. Then, the equations describing the operation of the DFIG in the synchronization mode based on the synchronous reference frame are (3-1) – (3-2). Since it is demanded the stator voltage equals to the grid voltage, i.e., $\overline{v_s} = \overline{v_g}$, then from (3-15), one obtains

$$\left. \begin{aligned} v_{s,d}^* &= |v_g| \\ v_{s,q}^* &= 0 \end{aligned} \right\} \quad (3-16)$$

- **Switching sequence**

The switching sequence of S_1 , S_2 and S_3 are shown in Figure 3-7. Under normal grid conditions, S_1 and S_2 are closed and S_3 is open. The DFIG is in DF mode. When a grid fault is detected, S_1 is switched off and S_3 is switched on, S_2 is kept closed. The crowbar is thus inserted into the stator circuit and the generator is switched to IG mode. When the grid voltage has recovered, S_2 is switched off and RSC is under synchronization control. S_1 is kept opened and S_3 is kept closed. After the

synchronization has been reached, the crowbar circuit is disconnected by opening S_3 . S_1 is reclosed and the generator is back to DF mode of connection.

Figure 3-7 Switching sequences of S_1 , S_2 and S_3 . (1 stands for switch on and 0 stands for switch off)

3.4 Control of crowbar resistance

Given the initial power P_d delivered to the grid and power factor (pf), the initial conditions of ω_r , i_s , i_r and v_r can be determined as shown in Appendix 3-B. Then using the derived expressions shown in Section 3.3, the transient rotor current passing through the RSC can be determined. This can be most conveniently illustrated using the numerical example of a DFIG which has the parametric values shown in Table 3-1.

Table 3-1 Parametric Values of a 1.5-MW, 60-Hz, 380-V 6-Pole Wound Rotor Induction Machine

Parameter	Value	Parameter	Value
L_m	2.9 p.u.	r_2	0.02 p.u.
L_1	3.09 p.u.	R_{CB1}	1.8 p.u.
L_2	3.09 p.u.	R_{syn}	10 p.u.
r_1	0.02 p.u.	V_{dc}	1150 V

Figure 3-8 Transient rotor current under a range of (a) initial active power P_d at pf = 1, (b) power factor for apparent power $S = 1$ p.u., (c) stator resistance for $S = 1$ p.u. and pf = 0.9 (leading) and (d) Crowbar resistance control for various initial P_d at pf = 0.9 (leading)

3.4.1 Transient Currents Limitation

Figure 3-8(a) shows the transient rotor current under a range of initial active power P_d . It shows that the higher the initial P_d , the larger would be the transient rotor current. When the DFIG output apparent power S is fixed at 1 p.u., Figure 3-8(b) shows the transient rotor current when the DFIG operates initially over a range of pf of between 0.9 (lagging) to 0.9 (leading). It is seen that larger transient current would occur under the leading pf operating conditions. Hence, the largest transient current would be under the highest initial S and at the pf of 0.9 (leading). This worst-case scenario was studied in greater detail by examining the effect of the effective stator resistance on the rotor transient current. The results are shown on Figure 3-8(c). The stator-side effective resistance includes the stator winding resistance which is 0.02 p.u.

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and the crowbar resistance which is assumed variable from 0 to 1.5 p.u. Thus $0.02 \leq R_s \leq 1.52$ p.u. The figure shows that the smaller the value of R_s , the higher would be the rotor transient current. Thus, the results suggest that transient rotor current can be reduced by increasing the stator resistance.

3.4.2 Control Strategy of Crowbar Resistance

Unfortunately, it is also noted that increasing the resistance leads to a longer settling time for the rotor current transients. A variable resistance scheme appears to be desirable. This possibility is explored, as follows.

Equation (3-13) shows that the ability of the generator to output active power to support the grid becomes less than desirable, if the crowbar resistance is kept high. Thus, at the early stage when the generator switches from the DF to IG mode, the SSC resistance should be kept high to limit the peak transient current. After the initial large transient current has been subdued, the resistance should be reduced so as to minimize the settling time of the current. Based on this observation, the strategy to adjust the resistance can be illustrated using the results of Figure 3-8(c). In view of the converter current limit, suppose the peak value of the transient current should not exceed 3 p.u. From Figure 3-8(c), a suitable initial crowbar resistance setting is 1.4 p.u. approximately. One convenient way to demonstrate the effect of the crow-bar resistance on the rotor current, as a function of elapsed time of the application of the resistance is shown on Figure 3-9. In this figure, the contours of rotor current of various levels are plotted as functions of the crowbar resistance and time. In this example for the case of rated output power at 0.9 leading pf, it shows that when the crowbar resistance is set at 1.4 p.u. for about 0.07 s, the rotor current is controlled and guaranteed to be below the 3 p.u. threshold. After 0.07 s, the peak value of the

transient current will be less than 3 p.u., regardless of the crowbar resistance. Thus, the crowbar resistance can be safely reduced after 0.07 s.

Figure 3-9 Control strategy of crowbar: $S=1.0$ and $\text{pf}=0.9$ leading

The strategy used in this study is to reduce the crowbar resistance linearly with time, after the initial high-resistance setting. The crowbar resistance can be adjusted in the manner of the curve ABCD shown in Figure 3-9. This method of crowbar resistance control can be designed for different initial P_d and pf conditions and a look-up table is constructed. This is shown in Figure 3-8(d) from which when the generator switches from DF to IG mode, the crowbar resistance control strategy shall be based on the initial P_d and the pf.

3.5 Simulation and experimental verification of MSDFIG for LVRT

3.5.1 Simulation results

The proposed mode switching method is illustrated using Matlab/Simulink to show the dynamic performance of the MSDFIG scheme. The DFIG wind power generation system examined is that shown in Figure 3-1, with the system parameters shown in Table 3-1. The worst-case scenario of $P_d=1$ p.u. at 0.9 leading pf is considered. A three-phase-ground fault close to the PCC occurs at $t=0.5$ s, and the appropriate CB operates to clear the fault at 1.12 s. S_I is reclosed at 1.18 s.

The waveform of the PCC voltage is shown on Figure 3-10(a). For the grid fault,

Figure 3-10 Profiles of (a) grid voltage; (b) rotor currents under DFIG and MSDFIG; (c) stator voltage waveform of MSDFIG and expanded plot; (d) active output power of MSDFIG; (e) reactive output power of MSDFIG; (f) DC-link voltage of MSDFIG (all plots in p.u. value)

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the rotor current of a conventional DFIG has also been calculated and is shown on Figure 3-10(b). It can be observed that the peak value of the DFIG rotor current increases to slightly over 3 p.u. The large grid transient voltage has resulted in undesirably large perturbations in the rotor current.

Consider the dynamic performance of the MSDFIG. The rotor current of the MSDFIG is also shown on Figure 3-10(b). When the generator switches from the DF to the IG mode, the rotor current oscillates and when the SSC is disconnected, the rotor current stabilizes. The current returns to the pre-fault value when the grid synchronization is completed. It can be readily seen that the peak value of the transient rotor current of the MSDFIG during this grid fault is less than 1.5 p.u. Compare this with the peak value of i_r of the conventional DFIG, it is concluded that the MSDFIG has indeed ridden through the grid fault much better than the conventional DFIG.

Figure 3-10(c) shows the stator voltage. When the grid fault occurs, the stator voltage reduces as the stator windings have been disconnected from the grid and the DFIG works in the IG mode. The stator voltage decreases gradually because of the SSC. When the resistance of the crowbar is reduced to zero, the stator voltage is almost zero and remains so until grid voltage has recovered after 1.12 s. It is also seen that because of the small resistance presence in the switches, the stator voltage in the IG mode still retains a small value but at a lower frequency of around 5 Hz. Successful synchronization is achieved in less than 0.04 s, following which the stator is re-connected to the grid and the stator voltage remains at the nominal value of 1 p.u.

The active and reactive power flows of the MSDFIG are shown in Figure 3-10(d) and Figure 3-10(e), respectively. It can be seen from Figure 3-10(d) that the active

power of MSDFIG in the IG mode of operation is kept below a level the converters can readily handle. After enduring a short period of well-damped oscillations during the synchronization stage, the active power is seen to recover to its pre-fault level. It shows that when the generator is in the IG mode of connection, it can still continue to deliver reactive power to the grid.

The DC-link voltage is shown in Figure 3-10(f): the voltage oscillates in an acceptable range which means that the active power generated by the DFIG can be delivered to the grid in the IG mode and the system is stable.

Another benefit of the proposed MSDFIG scheme is that when the grid voltage oscillates during fault conditions, the stator current can be controlled to a safe level because the stator circuit is isolated under the IG mode. This is unlike the case of a DFIG in which large transient stator current can appear and can be damaging to the generator. Figure 3-11(a) shows the grid voltage with a fault occurring at 0.5s, followed by a failed reclose action of the CB at 1.05s which causes a further round of

Figure 3-11 Comparison of (a) grid voltage, (b) stator current resulting from conventional DFIG and proposed MSDFIG schemes

voltage variation. Figure 3-11(b) shows the stator current waveforms of conventional DFIG as compared to that resulting from the proposed MSDFIG. It shows that the transient stator current of the conventional DFIG is much larger than that of the MSDFIG.

3.5.2 Experimental verification

Experimental verifications were carried out on a 1.5 kW DFIG to verify the effectiveness of the proposed MSDFIG technique. The experimental setup of the system is shown in Figure 3-12 and the parameters are given in Table 3-2. The prime mover is a dc machine controlled in torque producing mode to emulate the actions of the wind turbine. The grid is emulated by a controllable ac source (California Instruments 4500Ls). The experiments focused on the most important aspect of MSDFIG scheme which is the transient phenomenon when the MSDFIG switches from DF to IG mode. In order to simplify the hardware requirements, the GSC assigned for DC-link voltage control was replaced by a DC power supply with $V_{dc}=160$ V whereas the stator-side crowbar RCB was replaced by the constant resistor R_{es} as shown in Figure 3-12. The control system of RSC was implemented on a platform consisting of dSPACE 1104.

Figure 3-13 shows the performance of the DFIG system without the mode switching when the stator voltage experiences a 0.8 p.u. voltage dip. The rotor current can be seen increasing to some 250% of its pre-fault value over the transient period. This observation is in line with the aforementioned simulation results.

The proposed mode switching scheme was then implemented on the laboratory setup for

Table 3-2 Parametric Values of a 1.5-kW, 50-Hz, 220-V 4-Pole DFIG for Experiment

Parameter	Value	Parameter	Value
L_m	1.2 p.u.	r_2	0.023 p.u.
L_1	1.25 p.u.	V_{dc}	160 V
L_2	1.25 p.u.	r_1	0.023 p.u.

the same fault event. Figures 3-14(a) and (b) show the performance of the MSDFIG with $R_{es}=1.5$ p.u and $R_{es}=0.25$ p.u. respectively. In the IG mode, the stator frequency is kept at 5Hz so as to guarantee the rotor power flow is positive and is within the power rating of the RSC. It can be seen that the transient rotor current has been significantly reduced when the mode switching technique has been applied. Thus, the effectiveness of MSDFIG in improving LVRT performance has been demonstrated. Note that the rotor and stator currents shown in Figure 3-14(a) are lower than that shown in Figure 3-14(b). This is because the stator-side crowbar resistance value is higher in the former case. However, a longer settling time in the rotor current transients can be observed in Figure 3-14(a). These observations are consistent with the analysis and in agreement with the finding expressed in Figure 3-8(c).

Figure 3-12 (a) Schematic diagram of the experimental setup, (b) Photograph of the experimental setup

Figure 3-13 DFIG under three-phase 0.8 p.u. voltage sag: without mode switching

Figure 3-14 MSDFIG under three-phase 0.8 p.u. voltage sag: (a) Res=1.5 p.u.; (b) Res=0.25 p.u.

In conclusion, the effectiveness of the MSDFIG in mitigating the rotor-side overcurrent has been clearly demonstrated by the laboratory measurements and theoretical analysis of the effectiveness of the stator-side crowbar resistance has been validated.

3.6 Conclusion

The concept of MSDFIG is introduced and the DF and the IG modes of operation of the DFIG are studied. Based on the equivalent circuits of the two modes, the transient currents are evaluated when the DFIG switches from the DF to the IG and from the IG back to the DF modes. A possible technique of using stator crowbar to reduce the transient currents is proposed. The controllers of the GSC, RSC and crowbar in IG mode of connection are also described. In the IG mode of connection, both the active and reactive power flows through the back-to-back converters can be controlled and in this manner, the converters can be prevented from over-loading. A suitable strategy to adjust the stator crowbar resistance of the MSDFIG has been developed. A method to re-synchronize and re-connect the DFIG to the grid has also been proposed. It is shown that the method can effectively reduce the transient currents when the DFIG reverts back to the DF mode from the IG mode. Simulation study shows the MSDFIG is capable of riding through grid fault much more effectively and perform much better than the conventional DFIG. Experimental results have also been included to verify the effectiveness. However, there are potential shortcomings in the proposed LVRT scheme and those can be summarized as follows. Firstly, in order to achieve improved performance in an LVRT event, the resistor control of RCB needs to be performed and it is found to be a complex issue. Secondly, the control mode switch shown in Figure 3-5 gives rise to complications in the RSC controller.

Chapter 4. Mitigation of Unbalanced and Distorted

Stator Voltage of Stand-alone DFIGs Using

Repetitive Control

Unbalanced or non-linear loads result in distorted stator currents and electromagnetic torque pulsations in stand-alone DFIGs. This thesis proposes the use of a PIRC scheme to mitigate the levels of harmonics and unbalance at the stator terminals of the DFIG. The PIRC is structurally simpler and requires much less computation than existing methods. In this study, the PIRC is applied in time domain. Analysis of the PIRC operation and the methodology to determine the control parameters is included. Simulation study as well as laboratory test measurements demonstrate clearly the effectiveness of the proposed PIRC control scheme.

4.1 Introduction

The research efforts on the renewable and clean energy generation systems are receiving increasing attention globally. As one of the most attractive renewable energy sources, wind energy is well known for its low cost, high energy density and low pollution operational characteristics. Penetration of wind power world-wide is expected to reach 20% by 2030 and it will continue to contribute to the global electrical energy production in the future [1]. For the effective harnessing of wind power, variable speed constant frequency generators are always favored and for which DFIGs are used extensively in either stand-alone or grid-connected modes [1, 6, 14, 16-18, 25, 69-73]. As the power converters of the DFIG only handle part of the output power [69] and are therefore of lower power rating, DFIGs are economically

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attractive. Furthermore, DFIG enjoys higher efficiency because power loss in the converters is smaller due to the lower power rating of the converters.

DFIGs operating under grid-connected mode have attracted the majority of research interests so far. Issues related to low voltage ride through and active and reactive power control are predominantly addressed in the literature [6]. However, power systems in remote islands and rural areas require isolated generation systems to meet the electricity demand. There are many examples where such isolated systems are supplied by DFIG wind turbines [14, 16-18, 25, 69-71]. Furthermore, in the event of grid fault, a small islanded system may be formed from the large grid following the actions of protection scheme: thus, DFIG within the islanded system will need to operate in the stand-alone mode [72]. The stand-alone generator systems will have to operate with nonlinear and unbalanced loads connected to them. Such loads draw distorted or unbalanced currents which will result in distorted and unbalanced voltages at the stator terminals of the generators [73]. The negative phase sequence component and harmonic components of the distorted stator voltage would induce electromagnetic torque pulsations and excessive heat in the generators. Efficiency of the generators will reduce and the performance of other loads will be affected. Therefore, it is desirable to eliminate the negative phase sequence and harmonic components of the stator voltage in order to overcome such deficiencies.

A common approach for harmonic elimination is to use RC method [19-23]. RC is a technique based on the IMP [74] and is used specifically in tracking references or rejecting disturbances which occur periodically. The repetitive controller presents large gain at integral multiples of the fundamental frequency and is well known for its effectiveness in controlling harmonics [20]. A hybrid scheme which combines PI and

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RC techniques has been proposed in [19] in order to reduce the current harmonics of a DC/AC inverter. However, it has yet to be extended for the case of stand-alone DFIGs. In the present work, the proposed PIRC scheme is to eliminate the unbalanced and harmonic components of the stator voltage of a stand-alone DFIG. In synchronous reference frame, the fundamental components of the stator voltage are regulated by PI controllers while the unbalanced and harmonic components are to be eliminated through the application of RC technique. Compared to the control schemes described in [6, 16, 17, 70, 75], the advantages of the proposed control strategy can be summarized as follows:

- Both unbalanced and harmonic components can be eliminated by the same proposed controller, unlike existing methods where the components have to be dealt with separately. Thus, the proposed control scheme imposes much less computational burden;
- Regardless of the reference frame, the proposed controller can effectively deal with the periodic signals. This is unlike existing PI or PIR controllers in which the control systems have to be changed when using different reference frames.

In Section 4.2, the modeling of stand-alone DFIGs and the impacts of harmonics and unbalance stator voltage are explained. The proposed RC technique for harmonic elimination is given in Section 4.3. This is followed in Section 4.4 by the frequency response analysis of both steady and transient states of the proposed PIRC scheme. Simulation and laboratory test results to validate the effectiveness of the scheme are given in Sections 4.5 and 4.6 respectively.

4.2 Modeling and Control of Stand-alone DFIG

A typical configuration of stand-alone DFIG is shown in Figure 4-1 where loads, including non-linear and unbalanced loads, are shown inter-connected to the stator terminals of the DFIG. The rotor of the DFIG is interfaced through a back-to-back converter scheme. Conventionally, the LSC controls the DC-link voltage and the RSC controls the stator voltage.

4.2.1 Modeling of DFIG

The equivalent circuit of the DFIG in static stator-oriented reference frame is shown in Figure 4-2 in which the rotor variables are referred to the stator side [76]. $v_{s,s}$, $v_{r,s}$

Figure 4-1 Typical configuration of stand-alone DFIG connected to nonlinear and unbalanced loads

Figure 4-2 Equivalent circuit of the DFIG in stator reference frame

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, $i_{s,s}$ and $i_{r,s}$ represent the stator and rotor-side voltages and the stator and rotor currents in the stator reference frame. L_{ls} and L_{lr} are the stator and rotor leakage inductances. L_m is the magnetizing reactance. The dynamic behavior of the DFIG in the synchronous rotating reference is described by the following equations:

$$v_s = R_s i_s + \left(\frac{d}{dt} + j\omega_s \right) \lambda_s \quad (4-1)$$

1)

$$v_r = R_r i_r + \left(\frac{d}{dt} + j\omega_{sl} \right) \lambda_r \quad (4-2)$$

R_s and R_r are very small compared with the leakage inductances and could be ignored. λ_s and λ_r are the stator and rotor fluxes which can be determined using

$$\lambda_s = L_s i_s + L_m i_r \quad (4-3)$$

$$\lambda_r = L_r i_r + L_m i_s \quad (4-4)$$

where $L_s = L_m + L_{ls}$ and $L_r = L_m + L_{lr}$. Ignoring the voltage drop across the stator resistance and substituting (4-3) into (4-1), one can obtain the expression of stator voltage as

$$v_s = L_s \left(\frac{d}{dt} + j\omega_s \right) i_s + L_m \left(\frac{d}{dt} + j\omega_s \right) i_r \quad (4-5)$$

When the stator voltage is built up, the current is determined by the load conditions. From (4-3) and (4-4), the stator and rotor fluxes can be expressed as

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$$\lambda_s = \frac{L_m}{L_r} \lambda_r + \sigma L_s i_s \quad (4-6)$$

$$\lambda_r = \frac{L_m}{L_s} \lambda_s + \sigma L_r i_r \quad (4-7)$$

where $\sigma = 1 - L_m^2 / (L_r L_s)$. Substituting (4-7) into (4-2) one can obtain an expression for the rotor voltage as

$$v_r = \left(R_r + \sigma L_r \left(\frac{d}{dt} + j\omega_{sl} \right) \right) i_r + \frac{L_m}{L_s} \left(\frac{d}{dt} + j\omega_{sl} \right) \lambda_s \quad (4-8)$$

(4-1)-(4-8) constitute the DFIG model which will be discussed in Section 4.3.

4.2.2 Control of the Fundamental Component

The DC-link voltage of the DFIG system is controlled by the LSC while the rotor current, transferred into the rotor reference frame, is regulated by the RSC. Magnitude of the stator voltage $|v_s|$ is compared with its reference value and the error is inputted to a PI controller to obtain the reference value of $i_{r,q}$. The rotor current component aligned in d-axis, denoted as $i_{r,d}$, is regulated according to the d-axis stator current. This is in order to force the fundamental reference frame to align itself with the vector of stator flux [77]. Thus,

$$i_{r,d} = -\frac{L_s}{L_m} i_{s,d} \quad (4-9)$$

The fundamental component control of stand-alone DFIG system is explained in [78] and it is essential for the analysis of the controller in the following sections.

4.3 Co-ordinated control method development

4.3.1 Basic conception of RC

Periodic signals of period T can be generated by the system shown in Figure 2-17(a) while the basic RC loop is shown in Figure 2-17(b). The transfer function of RC loop is

$$G_{RC}(s) = \frac{O_{RC}(s)}{I_{RC}(s)} = \frac{k_{rc}G_f(s)Qe^{-sT}}{1 - Qe^{-sT}} \quad (4-10)$$

In general, zero steady-state error tracking of an external periodic input can be achieved by incorporating the RC scheme into a closed-loop system [59].

4.3.2 PIRC for RSC

In addition to control action on the fundamental component which is discussed in Section 4.1, the RC loop control is added to generate $v_{r,d,rc}$ and $v_{r,q,rc}$ that are responsible for stator voltage harmonic and unbalance compensation as shown in Figure 4-3.

As the DFIG is modeled using (4-1)-(4-8), in order to get the transfer function of the RSC controller, the DFIG block shown in Figure 4-3 can be mathematically represented by the DFIG model as shown in Figure 4-4 where $E_{r,dq}$ represent a disturbance. In Figure 4-4, in order to simplify the analysis, only the inner loop control is considered, i.e., only the rotor current control is analyzed in the fundamental component control. This is reasonable because if the rotor current control is achieved, the outer loop control which is discussed in Section 2.2.1 could also be obtained. In the DFIG model, G_a and G_b are obtained using (4-5) while λ_s is derived using (4-3).

Also, since the rotor voltage v_r is known, the rotor current i_r can be obtained using (4-8). Hence, G_c and G_D can be determined. The controller G_{PI} in Figure 4-4 is to effect changes in the fundamental component of the generator stator voltage and details on the design of G_{PI} can be found in [78]. G_{RC} represents the transfer function of the RC loop which is introduced to control the harmonic components of the stator voltage. The output signal $v_{r,rc}$ of the RC loop is generated from the stator voltage, as highlighted in Figure 4-3. From Figure 4-4, the closed-loop transfer function of the stator current is

Figure 4-3 Proposed RSC controller for stand-alone DFIG connected to unbalanced and non-linear loads

Figure 4-4 Block diagram of stator voltage controller

$$v_{s,dq}(s) = G_1 i_{r,dq}^*(s) + G_2 E_{r,dq}(s) + G_3 i_{s,dq}(s) \quad (4-11)$$

where G_1 , G_2 and G_3 represent the transfer functions from the reference rotor current, rotor voltage disturbance and stator current to the stator voltage respectively. Using Figure 4-4 and in the design of the stator voltage controller without the RC loop, the stator voltage is given by

$$v_{s,dq}(s) = \frac{G_{PI} G_D G_a}{1 + L_m G_c G_D + G_{PI} G_D} i_{r,dq}^*(s) + \frac{G_D G_a}{1 + L_m G_c G_D + G_{PI} G_D} E_{r,dq}(s) + \left(\frac{-L_s G_c G_D G_a}{1 + L_m G_c G_D + G_{PI} G_D} + G_b \right) i_{s,dq}(s) \quad (4-12)$$

With the RC loop in the controller of RSC, from Figure 4-4, the transfer functions pertaining to (4-11) can be expressed as

$$G_1 = \frac{v_{s,dq}(s)}{i_{r,dq}^*(s)} = \frac{H(s) G_{PI}(s) (1 - Qe^{-sT})}{1 - (1 - k_{rc} G_f(s) H(s)) Qe^{-sT}} \quad (4-13)$$

$$G_2 = \frac{v_{s,dq}(s)}{E_{r,dq}(s)} = \frac{H(s) (1 - Qe^{-sT})}{1 - (1 - k_{rc} G_f(s) H(s)) Qe^{-sT}} \quad (4-$$

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14)

$$G_3 = \frac{v_{s,dq}(s)}{i_{s,dq}(s)} = \frac{(G_b - H(s)L_s G_c)(1 - Qe^{-sT})}{1 - (1 - k_{rc}G_f(s)H(s))Qe^{-sT}} \quad (4-15)$$

In (4-13)-(4-15), $H(s)$ is

$$H(s) = \frac{G_D G_a}{1 + L_m G_c G_D + G_{PI} G_D} \quad (4-16)$$

Based on equations (4-12)-(4-16), an analysis to determine suitable control parameters for the proposed control scheme for the RSC can be carried out, as follows.

4.4 Design of PIRC

The design of the PIRC is to meet the following requirements: the output $v_{s,dq}(s)$ needs to follow the rotor current reference; the harmonics and negative phase sequence components of the stator voltage are to be minimized. In the following, determination of the parametric values of the PIRC will be discussed with the view to meet these requirements. In essence, the PI controller $G_{PI}(s)$ shown in Figure 4-4 is designed first and from which, the determination of the parameters k_{rc} , Q and G_f of the RC controller G_{RC} are carried out in order to guarantee acceptable stability and performance of the PIRC. This is detailed in Section 4.4.1. The steady-state analysis given in Section 4.4.2 shows the effectiveness of PIRC. A general approach to design the PIRC is illustrated in Section 4.4.3.

4.4.1 Stability Analysis

The performance and the determination of suitable parametric values for the PIRC

will be analyzed based on (4-12)-(4-15). Firstly the PI controller in Figure 4-4 would be designed to achieve desired dynamic and steady state performance of the conventional control system before the parameters of the RC loop are determined to guarantee stability of the PIRC system. The characteristic equation of (4-12) is given by

$$D(s) = L_s L_r s^2 + (L_s R_r + L_s k_p + j\omega_{sl} L_s L_r) s + L_s k_i \quad (4-17)$$

The corresponding Routh table is shown in the Appendix 3-A and based on Routh-Hurwitz stability criterion, when k_p and k_i are positive, stability of the stator voltage control scheme will be guaranteed.

With stability of the system described by (4-12) guaranteed, then according to (4-13)-(4-15) the PIRC system is stable if (4-18) is satisfied:

$$\left\| 1 - (1 - k_{rc} G_f(s)) H(s) Q e^{-sT} \right\| \neq 0, \quad s = j\omega \quad (4-18)$$

where $\left| e^{-sT} \right| = \left| e^{-j\omega T} \right| = 1$. It can be readily shown that the condition (4-18) will be met if

$$\left| 1 - k_{rc} G_f(j\omega) H(j\omega) \right| < \frac{1}{|Q|}, \quad \omega \in \left[0, \frac{\pi}{T} \right] \quad (4-19)$$

where $Q \neq 0$, $T = 1/f$, $G_f(j\omega) = e^{j\theta}$. f is the fundamental frequency and θ is the compensation angle of RC loop.

Figure 4-5 provides a geometric explanation of (4-19) and can be used to help determine k_{rc} . The condition (4-19) can be explained as the tip of the vector OK ,

which represents $k_{rc}G_f(j\omega)H(j\omega)$ in Figure 4-5, is within the circle which has the radius $1/Q$ and center $C(1,0)$. For example, as shown in the figure, OK satisfies the stability condition when $Q=0.8$ but not when $Q=1.2$. Thus stability margin would be reduced when Q is increased and causes the selection of k_{rc} to be increasingly more difficult. Thus, it can be shown that k_{rc} must satisfy the condition

$$\left|k_{rc}G_f(j\omega)H(j\omega)\right| = |OK| < 2|OC|\cos\varphi \quad (4-20)$$

Figure 4-5 Stability condition for k_{rc} determination

As shall be seen in the next section when using steady-state analysis, harmonics cannot be completely eliminated with $Q < 1$. In order to meet this harmonics elimination requirement, the limiting case would be when $Q=1$. Hence, for this extreme condition, k_{rc} should be within the range

$$k_{rc} < \frac{2\cos\varphi}{\left|G_f(j\omega)H(j\omega)\right|} \quad (4-21)$$

where $\varphi = \angle G_f(j\omega)H(j\omega)$. The range of φ varies as Q changes. For example, if

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$Q=1$, φ should satisfy the condition

$$\varphi \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right) \quad (4-22)$$

In examining (4-21), it is noted that $H(j\omega)$ has been determined during the design of the PI controller $G_{PI}(s)$, then, the lead compensator $G_f(j\omega) = e^{j\theta}$ needs to be designed to satisfy (4-22). $G_f(j\omega)$ could be designed for $\varphi=0$ at the fundamental frequency. Substituting $s = j\omega$ into (4-16), one can obtain the value of $|G_f(j\omega)H(j\omega)|$. Using (4-21), the range of value for k_{rc} can be determined.

4.4.2 Steady-State Analysis

Next, the frequency response of the closed-loop control system of DFIG is investigated, with the view to achieve zero steady-state harmonic levels. In the stand-alone DFIG system, harmonics appear in the stator current i_s . Substituting $s = \pm n\omega_s$ ($n=1, 2, \dots$) into (4-12), it is noted that $v_{s,dq}(n\omega_s) \neq 0$ if $i_{s,dq}(n\omega_s) \neq 0$. Furthermore, the harmonics in the disturbance E_r and harmonics in rotor current i_r would also distort the stator voltage. By substituting $s = \pm n\omega_s$ ($n=1, 2, \dots$) into (4-15) and as $|e^{-jn\omega_s T}| = 1$, so when $Q=1$, the closed-loop transfer function G_3 at the integer multiples of the fundamental frequency is 0, i.e.

$$G_3(s)\Big|_{s=\pm jn\omega_s} = 0 \quad (n=1, 2, \dots) \quad (4-23)$$

That is, with the RC loop incorporated in the RSC, (4-23) shows that the harmonic components of the stator current which are integer multiples of the fundamental

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frequency will no longer distort the stator voltage.

Similarly, it is seen that G_1 and G_2 at $s = \pm n\omega_s$ ($n = 1, 2, \dots$) is also 0, i.e.

$$G_1(s) \Big|_{s=\pm jn\omega_s} = 0 \quad (n = 1, 2, \dots) \quad (4-24)$$

$$G_2(s) \Big|_{s=\pm jn\omega_s} = 0 \quad (n = 1, 2, \dots) \quad (4-25)$$

Again (4-24) and (4-25) show that the harmonic components of the reference rotor current and disturbance signals in the rotor voltage, which are integer multiples of the fundamental frequency, will not appear in the stator voltage.

As a result, harmonics in the stator voltage of the stand-alone DFIG shall be effectively eliminated.

4.4.3 A General Approach to Design the PIRC

The analysis of Section 4.4.1 shows that k_p and k_i must be positive to guarantee stability of the stator voltage control scheme at the fundamental frequency. The general approach to the design of the complete PIRC can now be illustrated using the example shown in Table 4-1. The parametric values shown there are quite representative for a typical DFIG. Indeed, the simulation and experimental test results shown in Sections 4.5 and 4.6 are based on the same DFIG parameters.

Accordingly and using these DFIG parameters, based on the analysis in Section 4.4.1 suppose the PIRC is designed to achieve an open-loop crossover frequency of

Table 4-1 Parameters of DFIG for simulation and experimental test

Parameters	Simulation	Experiment
Rated power	1.5 MW	1.5 kW
f	50 Hz	50Hz
V_{rated}	380 V	220 V
V_{dc}	300 V	160 V
L_m	2.95 p.u.	1.2 p.u.

250Hz It results in $k_p=0.3$, $k_i=10$. Then based on (4-21), the gain of the RC is selected to meet the condition $k_{rc}<0.3$.

Figure 4-6 Frequency response of (a) RC with variable k_{rc} at $Q=1$ and (b) RC with variable Q at $k_{rc}=0.2$, (c) G_1 , (d) G_2 and (e) G_3 with and without RC loop

Figure 4-6 shows the Bode diagram of the RC controller as expressed by (4-10) for a range of values of k_{rc} and Q . Figure 4-6(a) shows that the bandwidth of the controller at each harmonic frequency is determined by k_{rc} : the bandwidth increases with k_{rc} although it should concurrently satisfy (4-21). Figure 4-6(b) shows that the

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gain of RC loop increases with Q . For example, at $Q=1$, RC has large gain at harmonic frequencies but for $Q=0.6$, the gain decreases to -10dB. So in the following analysis, $k_{rc}=0.2$ and $Q=1$ are selected. Most importantly, from Figure 4-6(a) and 4-6(b), it is observed that when the parameters are properly selected, the RC presents large gains at integer multiples of the fundamental frequency, which means that it is possible for the proposed scheme to reject periodic harmonic components.

The frequency responses of G_1 , G_2 and G_3 are shown in Figure 4-6(c)-(e). Compared with the conventional PI control, the PIRC controller can eliminate the harmonics and unbalanced components because the frequency responses of G_1 , G_2 and G_3 equal to 0 at integer multiples of the fundamental frequency. It indicates that with the PIRC, the harmonic components caused by rotor current, disturbance signals and stator current can be mitigated.

4.5 Simulation results

A stand-alone DFIG with the parameters shown in Table 4-1 is modeled using Matlab/Simulink. The proposed PIRC is applied in the RSC control. Various conditions of non-linear and unbalanced load connected to the PCC are simulated. In this study, the fundamental component of the stator voltage is controlled to be 0.8 p.u.

4.5.1 With non-linear load

A three-phase full-bridge diode rectifier with a resistive load is connected at the PCC. As described in Section 4.2, the harmonics with $6n\pm1$ multiples of fundamental frequency would appear in both the stator current and voltage. The distorted stator voltage can be mitigated using PIRC.

Figure 4-7 Simulation results: (a) rotor current, (b) magnitude of 5th and 7th harmonic components of stator voltage (c) phase “a” stator voltage and (d) phase “a” stator current under nonlinear load condition under conventional control and that under PIRC (All quantities are in p.u.), (e) FFT analysis of stator voltage and (f) rotor current.

The performance of the PIRC applied in the stand-alone DFIG with a 0.8 p.u. rotor speed is shown in Figure 4-7. In this figure, the first 0.1s is simulated with the application of the conventional PI controller and the next 0.1s is with the PIRC. In Figure 4-7(a), the rotor current is distorted when the conventional controller is applied which verifies the analysis in Section 4.2. However, with the PIRC, the compensation signal added in the rotor current leads to significant reduction in stator voltage harmonic components as shown in Figure 4-7(b). The magnitudes of the 5th and 7th harmonic components are shown in Figure 4-7(b). In conventional controller, both the 5th and 7th harmonics are greater than 0.05p.u. and the THD is as large as 13%. With the PIRC, the magnitudes of the 5th and 7th harmonics are reduced to around 0.02p.u. while the THD is at a much lower value of some 3.5%. The waveform of phase “a” stator voltage shown in Figure 4-7(c) reveals that distortion in the stator voltage has been reduced with the use of the PIRC. The stator current is as shown in Figure 4-7(d). The frequency spectrums of stator voltage and rotor current are shown in Figure 4-7(e)

and 4-7(f), respectively. According to Figure 4-7(e), it can be found that the harmonic component in stator voltage is reduced significantly.

4.5.2 With unbalanced load

In this case, a three phase unbalanced resistive load is connected to the PCC, as a consequence of which an unbalanced stator current is produced. It results in a negative phase sequence component in the stator voltage.

Figure 4-8 Simulation results: (a) positive phase sequence component magnitude of v_s , (b) negative phase sequence component magnitude of v_s , (c) three phase stator voltage and (d) phase "a" rotor current under unbalanced load condition under conventional control and that under PIRC (All quantities are in p.u.), (e) FFT analysis of rotor current.

The performance of the PIRC for unbalanced stator voltage compensation is shown in Figure 4-8. The conventional controller is applied in the first 0.1s and the PIRC is used in the next 0.3s. The magnitudes of the positive and negative phase sequence components of the stator voltage are shown in Figure 4-8(a) and Figure 4-8(b), respectively. The positive phase sequence component of the stator voltage is maintained at around 0.8 p.u. in both the conventional controller and PIRC. The negative phase sequence component is reduced from 0.13 p.u. when using the

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conventional controller to less than 0.01 p.u. when PIRC is applied. The three phase waveforms of the stator voltage are shown in Figure 4-8(c) and it shows that the unbalanced stator voltage has been significantly reduced. The rotor current and its frequency spectrum is shown in Figure 4-8(d) and 4-8(e), respectively. Similar to Figure 4-7(a), the rotor current is distorted when conventional controller is used but with the PIRC control, compensation component is added into the rotor current.

Based on the results of Figure 4-7(a) and Figure 4-8(d), it can be concluded that in order to compensate for the $6n \pm 1$ order harmonics and unbalanced components, compensation components of different frequencies need to be used.

4.6 Experimental results

To verify the effectiveness of the proposed PIRC technique, experimental verifications are carried out with a 1.5 kW stand-alone DFIG. The experimental setup of the system is shown in Figure 4-9. Both the PI and PIRC schemes are tested. In order to simplify hardware requirements, the LSC assigned for DC-link voltage control is replaced by a DC power supply with $V_{dc} = 160$ V. So in this study, only RSC is controlled with the proposed controller as shown in Figure 4-3. The control system is implemented on a platform consisting of dSPACE1104 microcontroller and a programmable logic device. The switching frequency of RSC is kept at 5 kHz. The nonlinear load is a full-bridge diode rectifier connected to a series-connected resistor-inductor bank. The unbalanced load is implemented through manipulating a three-phase adjustable resistance bank. The rotor speed is maintained at 0.8 p.u. In carrying out the tests, firstly adjust the input DC voltage of a DC machine which is used as the prime mover to achieve the rotor speed of 0.8 p.u. Then the PI or PIRC RSC controller is switched on to maintain the stator voltage under different load conditions.

Figure 4-9 Experimental setup of a 1.5-kW stand-alone DFIG

4.6.1 With non-linear load

When the three-phase diode rectifier with resistive load is connected at the PCC, the phase “a” stator voltage and rotor current are recorded. In this scenario, the nonlinear load is a 50Ω resistor and a 20mH inductor connected with a diode rectifier. See the results of Figure 4-10. When the DFIG is under conventional PI control, the stator voltage in Figure 4-10(a) and the rotor current are seen to be highly distorted. The stator voltage of the stand- alone DFIG under PIRC control is shown in Figure 4-10(b). The harmonic components are significantly reduced while the fundamental

Figure 4-10 Rotor current and stator voltage with (a) conventional controller and (b) PIRC with a non-linear load connected at the PCC

component is maintained constant. As the compensation signal is included, the rotor current is distorted in the PIRC scheme.

4.6.2 With unbalanced load

When unbalanced loads are connected at the stator, the three phase stator voltage and phase “a” rotor current are shown in Figure 4-11. Figure 4-11(a) shows the stator voltage with one phase connected with a heavier load, i.e. the resistors at Phase A is 15Ω and at Phase B and C are both 50Ω . In this case, the stator voltage is unbalanced and the rotor current is distorted. When the PIRC is applied, as shown in Figure 4-

11(b), the unbalanced stator voltage is significantly compensated. When one phase is connected with a lighter load, the stator voltage of stand-alone DFIG under conventional controller and PIRC are as shown in Figure 4-11(c) and (d), respectively. In this scenario, Phase A is connected with an 80Ω resistor and Phase B and C are 40Ω . In this case, the stator voltage is much balanced with the use of the PIRC control. Comparing the rotor current with PIRC under non-linear load and unbalanced load conditions, it can be seen that the frequencies of control signal needed for harmonic compensation and negative phase sequence component compensation are quite different. Finally, the efficacy of the proposed PIRC control scheme is clearly verified for harmonic rejection and unbalanced voltage compensation in stand-alone DFIG

Figure 4-11 Rotor current and stator voltage under unbalanced load conditions with a heavier load connected to one phase: under (a) conventional controller and (b) PIRC; with a lighter load connected to one phase: under (c) conventional controller and (d) PIRC.

experimentally.

4.6.3 With combined non-linear and unbalanced loads

The experimental results under the combined non-linear and unbalanced loads condition are shown in Figure 4-12. Figure 4-12(a) shows that the unbalanced and harmonic components are present in the stator voltage with the conventional PI controller. According to Figure 4-12(b), it can be readily seen that the negative phase sequence and harmonic components are reduced when PIRC is applied in the RSC controller. Therefore, it demonstrates clearly the PIRC is effective in providing both unbalanced and distorted stator voltage compensation.

Figure 4-12 Rotor current and stator voltage with (a) conventional controller and (b) PIRC with combined non-linear and unbalanced loads connected at the PCC

4.7 Conclusion

Stand-alone DFIGs are used in power generation in many situations. The stator voltage of the DFIG may be distorted by non-linear or unbalanced loads. In order to prevent such voltage distortions and hence reduce their negative impacts, PIRC is proposed in this thesis for mitigating the levels of the voltage unbalance and harmonics. The impact of these voltage components on the output performance of the

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DFIG is also analyzed through transforming them into periodic components of corresponding frequencies in the synchronous reference frame. The RC technique is then employed to eliminate the periodic components. A single RC can compensate both the harmonic and negative sequence components which are integer multiples of the fundamental frequency and therefore, the controller is structurally simpler compared to existing conventional control schemes which are developed in their respective harmonic reference frames. The superior performance of the proposed control scheme is verified by a series of simulation study and experimental tests.

Chapter 5. Power Quality Improvement of DC-microgrid with DFIG Based Wind Power Generation

A novel DFIG connection configuration is proposed in order to maintain the advantages of DFIGs when they are connected to the DCMG. Accordingly, the harmonic problem in the proposed configuration has been discussed. The harmonics of stator current are eliminated by using RC in the RSC controller. A SC is proposed to eliminate the harmonics in the stator power using repetitive control. The efficiency of DFIG can be maintained at a higher value and the MPPT can still be achieved by installing a battery energy storage system into each node. Furthermore, when the BESS is fully charged or cut off due to fault conditions, the DFIG can be operated to maintain the local voltage by switching the control mode of RSC so that the reliability of the system can be increased.

DFIG is one of the most widely used wind power generators worldwide due to the low cost and flexible controller. With the rapid development in DCMG, more and more attention has been focused on the interconnection between DFIG and DCMG. However, the DFIG will lose its benefits by using the conventional configuration. Therefore, a novel configuration of DFIG is proposed in this thesis to solve this problem. The harmonic problem has been solved and the efficiency of the generator has been improved by the proposed techniques. Therefore, the proposed configuration is realistic.

5.1 Introduction

Harmonics appear in both the stator current and stator power in the proposed DFIG configuration because of SSR. Certain control methods for stator current harmonic elimination of DFIG have been developed in [15, 32, 33, 77, 79-83]. In [80], to eliminate the harmonic components, the corresponding commanded value of rotor current is calculated using the parameters of the generator and the harmonic components of the grid voltage. In this method, harmonics could be eliminated when the rotor current tracks the commanded value but the performance of this controller is limited by the speed of the controller and the accuracy of the commanded values. In practice, the parameters of the generator may change in value due to operating conditions and aging and it becomes difficult to achieve effective harmonic elimination using this method. In [15, 32], the stator current harmonic components extracted from BPF are transformed into DC values in the corresponding dq reference frames and are controlled with the use of a PI controller. In this method, the harmonic components in stator current could be eliminated but it requires a large number of calculations because the controller of each order of harmonic component requires a BPF, a dq frame transformation and a reverse dq frame transformation back to the corresponding rotating frequency. The parameters of each PI control loop should be determined carefully in order to guarantee the stability and dynamics of the control system. Recently, PIR control technique has been proposed for harmonic elimination of DFIG systems [33, 77]. The 5th and 7th harmonic components of stator current in grid connected DFIGs [33, 82] and those of stator voltage in stand-alone DFIGs [77] are eliminated by using a PIR controller. But the performance of this controller is limited when some higher order harmonic components are contained in the stator voltage. In order to overcome the shortages of the aforementioned methods, the

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harmonic elimination of stator current is achieved by using RC in the RSC controller in this chapter.

The harmonic elimination of output power of DFIG by control of RSC using PIR control has been discussed in [80]. The shortages of PIR control have been discussed as aforementioned and thus, RC will be applied in the controller. An additional super capacitor is required to connect to the DFIG for purpose of stator power harmonic elimination.

The efficiency of the generator is another concern when it is connected to the DCMG. It is proposed in this chapter that a battery energy storage system (BESS) is interfaced to the DCMG for the purpose of power buffering. In such a case, the grid voltage can be maintained with the control of BESS and the DFIG would be able to perform MPPT in order to achieve a greater efficiency.

In order to improve the reliability of the system, when the BESS is fully charged or out of service due to fault conditions, the DFIG will be switched to a control mode where the local DC voltage is regulated to achieve DC voltage droop control. With this proposed control, the system can be kept stable even the BESS is out of service.

The organization of this chapter is as follows. In Section 5.2, the configuration of the proposed DCMG connected with loads and distributed sources consisted by BESSs and DFIGs is introduced. The harmonic problem in the stator current and output power is discussed in Section 5.2 and 5.3, respectively and accordingly, a RC technique of RSC and SC for harmonic elimination is proposed. The discussion on control mode selection of control of RSC and BESS is given in Section 5.4.

Simulation results are shown in Section 5.5 to verify the effectiveness of the proposed controllers.

5.2 DCMG with distributed generators and loads

Figure 5-1 DC microgrid

A generic DCMG integrated with sources and loads is shown in Figure 5-1. Each node consists of a local source and loads. The sources can be renewable energy like DFIGs or traditional energy like fossil fuel generators. It is proposed in this research that the local voltage is maintained by the control of local source to achieve an improved voltage droop control [12]. When the DFIG is connected to the DCMG, the DFIG would lose certain benefits from economic point of view if the conventional connection scheme is used. In the conventional connected DFIG, a fully rated converter is required to transfer power from AC side to DC side. As a result, PMSG will be more attractive than DFIG because of PMSG has a lower cost and easier control. However, this limitation could be avoided by reconfiguration the DFIG in DCMG as shown in Figure 5-2, where the DFIG in DCMG is configured such that the

stator is connected to the DC grid through an uncontrollable three phase diode rectifier. In such a situation, a fully controllable grid-side converter is saved compared to the case of conventional DFIG system. Therefore, the proposed system can still keep the economic advantages.

Figure 5-2 Distributed DFIG with power buffer and local load

In order to maintain a higher efficiency of the DFIG, MPPT is carried out with the help of a battery energy storage system (BESS) at the local node. The local DC voltage is maintained by controlling the DC-DC converter interfacing BESS. The control of DFIG will be switched to local voltage control mode if the BESS is fully charged or discharged due to long-term mismatch between the power generation and load demand. When the load demand is lower than the active power generated by the DFIG, BESS absorbs power. When the load demand is higher than that is generated by the DFIG, BESS supplies the deficit so as to maintain the power balance in the

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system. As a result, MPPT can be achieved and a higher power efficiency of the DFIG can be maintained.

The details of each node are shown in Figure 5-2. In each node, the source consists of a DFIG and a BESS. The stator of the DFIG is connected to the DCMG through a stator-side rectifier (SSR).

Although the SSR could save the cost of the generation system, it leads to large distortions in the stator voltage [34]. The harmonic components of stator voltage would also cause harmonics in the stator current. The harmonic components are harmful for the DFIG and they degrade its power efficiency. Therefore, a PI controller with resonant loop (PIR) [34] is proposed to eliminate the stator current harmonics of the DFIG in this configuration.

Due to distorted stator current, harmonic components would also appear at DC side (i_{s-DC}). Although harmonics would be present at DC side of RSC (i_{r-DC}), their magnitude is smaller as rotor current is much smaller than the stator current. Therefore, elimination of harmonics in i_{s-DC} has an enormous effect on the power quality than the elimination of harmonics in i_{r-DC} . In order to mitigate harmonics in i_{s-DC} , a SC is connected to the DCMG through a DC-DC converter. The controller of the DC-DC converter for harmonic elimination will be discussed in great detail in the following sections.

In DCMG, changing load demand could sometimes cause power unbalanced. Certain load demands lead to unbalanced load sharing among sources. When the DFIG is controlled for MPPT, in some nodes with heavy loads, the BESS could be fully discharged and the DC voltage cannot be maintained due to not sufficient power. While in some nodes with very light loads or no loads, the BESS may be fully

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charged and the output power of the source can become higher than the load demand leading to an increased DC voltage. Thus, an improved droop control scheme for DC voltage is proposed in this paper for the purpose of equitable load sharing and maintaining the DC voltage.

5.3 Mitigation of Harmonics of stator current

5.3.1 Modeling of DFIG

The generator model in synchronous reference frame is given by

$$v_{s,dq} = R_s i_{s,dq} + j\omega_s \lambda_{s,dq} + \frac{d}{dt} \lambda_{s,dq} \quad (5-1)$$

$$v_{r,dq} = R_r i_{r,dq} + j\omega_{sl} \lambda_{r,dq} + \frac{d}{dt} \lambda_{r,dq} \quad (5-2)$$

The stator and rotor fluxes are defined as

$$\lambda_{s,dq} = L_s i_{s,dq} + L_m i_{r,dq} \quad (5-3)$$

$$\lambda_{r,dq} = L_r i_{r,dq} + L_m i_{s,dq} \quad (5-4)$$

The stator and rotor flux, stator current and rotor voltage can be calculated as

$$\lambda_{r,dq} = \frac{L_m}{L_s} \lambda_{s,dq} + \sigma L_r i_{r,dq} \quad (5-5)$$

$$i_s = -\frac{L_m}{L_s} i_r + \frac{1}{L_s} \lambda_s \quad (5-6)$$

$$\lambda_s = \frac{1}{s + j\omega_s} v_s \quad (5-7)$$

$$v_r = \frac{L_m}{L_s} (s + j\omega_{sl}) \lambda_{s,dq} + (R_r + \sigma L_r (s + j\omega_{sl})) i_{r,dq} \quad (5-8)$$

The following analysis will be based on this model of DFIG.

5.3.2 Harmonic Problem of DFIG

As described in Section 5.1, the induction generator is connected to the DCMG using a three-phase diode bridge rectifier. The details of SSR are shown in Figure 5-3. The conduction sequence of the diodes is shown in Figure 5-4(a). Then, the phase to phase voltages could be derived according to the order of diode conduction and are shown in Figure 5-4(b). As the stator voltages are balanced, the phase voltages could be derived and phase-a voltage is shown in Figure 5-4(c). It could be found that the stator voltage is largely distorted. After Fourier series expansion, the stator voltage can be expressed as shown in (5-9).

$$v_s(t) = \sum_{n=1}^{\infty} a_n \sin 2n\pi ft \quad (5-9)$$

Figure 5-3 SSR of the DFIG

Figure 5-4 (a) Diode conduction sequence, (b) waveform of stator phase to phase voltage, (c) waveform of stator phase voltage

where a_n represents the amplitude of the n^{th} harmonic and n is the harmonic order. f is the frequency of the fundamental component of stator voltage. The amplitude of each order of harmonic could be calculated using

$$a_n = 2f \int_0^T v_s(t) \sin 2\pi n f t \, dt \quad (n=1, 2, \dots) \quad (5-$$

10)

where $T=1/f$. From (5-10), the following Fourier coefficients can be determined, $a_1=0.6366$, $a_5=0.1273$, $a_7=0.0909$, $a_{11}=0.0579$, $a_{13}=0.0490$, $a_{17}=0.0375$ and $a_{19}=0.0335$. It is clear that the stator voltage not only contains the 5th and 7th harmonic components, but also 11th, 13th, 17th and 19th harmonics as well. The magnitudes of higher order harmonics are significant and cannot be ignored. Thus, the compensation methods presented in [33, 77] that only focus on the 5th and 7th harmonic components may not perform very well.

Figure 5-5 Equivalent circuit of the DFIG

The stator current would be distorted when stator voltage contains large amount of harmonics. As shown in Figure 5-5, in steady state, when the voltage drop across the stator resistor is ignored, the induced EMFs in the stator and rotor E_1 and E_2 are also distorted. Thus, if the rotor-side injection voltage v_r generated by rotor-side converter is purely sinusoidal, the difference between distorted induced EMF in rotor E_2 and sinusoidal rotor voltage v_r would lead to large harmonics in both rotor and stator current. These harmonics would seriously deteriorate the power quality and the efficiency of the DFIG. Therefore, the elimination of these harmonics is an essential task for improving the efficiency of the DFIG. A strictly sinusoidal stator current could ensure balanced heating and lower harmonic losses in the three-phase stator windings.

Therefore, in order to guarantee the efficiency of the DFIG in the proposed configuration, the harmonic components present in the stator current need to be eliminated.

5.3.3 Harmonic Elimination Control Scheme

The control scheme with RC loops for the DFIG is shown in Figure 5-6, where k_{rc} is the gain of RC, $G_f(s)$ is a phase lead compensator and Q is a low-pass filter which could set to be a constant [20]. The fundamental component control will be discussed

According to the IG model shown in (5-5)-(5-8), the schematic representation of the current control loop of the DFIG is shown in Figure 5-7, where $E_{r,dq}$ is represented as a disturbance. According to Figure 5-7, we denote $G_D(s)=1/(\sigma L_r s + R_r + j\omega_{sl}\sigma L_r)$, $G_{PI}(s)=k_p+k_i/s$, $G_a(s)=1/(s+j\omega_s)$, and $G_b(s)=(s+j\omega_{sl})L_m/L_s$. The closed-loop transfer function of stator current is determined as

$$i_{s,dq}(s) = -G_{i1}i_{r,dq}^*(s) + G_{i2}E_{r,dq}(s) + G_{i3}v_{s,dq}(s) \quad (5-12)$$

where G_{i1} , G_{i2} and G_{i3} are the transfer functions from commanded rotor current, input rotor voltage disturbances and stator voltage to actual stator current respectively. In conventional controller without the RC loop, the expression of stator current is given in (5-13) with the help of Figure 5-7.

$$i_{s,dq}(s) = \frac{-\frac{L_m}{L_s}G_D G_{PI}}{1+G_D G_{PI}}i_{r,dq}^*(s) - \frac{\frac{L_m}{L_s}G_D}{1+G_D G_{PI}}E_{r,dq}(s) + \left(\frac{\frac{L_m}{L_s}G_a G_b G_D}{1+G_D G_{PI}} + \frac{1}{L_s}G_a \right)v_{s,dq}(s) \quad (5-13)$$

With the RC loop, according to Figure 5-7, the transfer functions in (5-12) could be expressed as

$$G_{i1} = -\frac{i_{s,dq}(s)}{i_{r,dq}^*(s)} = \frac{H(s)G_{PI}(s)(1-Qe^{-sT})}{1-(1-k_{rc}G_f(s)H(s))Qe^{-sT}} \quad (5-14)$$

$$G_{i2} = \frac{i_{s,dq}(s)}{E_{r,dq}(s)} = \frac{-H(s)(1-Qe^{-sT})}{1-(1-k_{rc}G_f(s)H(s))Qe^{-sT}} \quad (5-15)$$

$$G_{i3} = \frac{i_{s,dq}(s)}{v_{s,dq}(s)} = \frac{(H(s)G_a G_b + G_a/L_s)(1-Qe^{-sT})}{1-(1-k_{rc}G_f(s)H(s))Qe^{-sT}} \quad (5-16)$$

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where

$$H(s) = \frac{L_m}{L_s} \times \frac{G_D}{1 + G_D G_{PI}} \quad (5-17)$$

As the transfer function of the DFIG controlled with PIRC system is derived, the performance and stability of the system will be analyzed in the following section.

5.3.4 The PIRC System Analysis

The stability analysis can be performed using the method introduced in Section 5.4.1. So that the stability margin of k_{rc} can be derived as

$$k_{rc} < \frac{2 \cos \varphi}{|G_f(j\omega)H(j\omega)|} \quad (5-18)$$

where $\varphi = \angle G_f(j\omega)H(j\omega)$.

$H(j\omega)$ is determined by the PI controller which should be first designed to achieve a good performance of the fundamental component tracking.

The frequency response of the closed-loop system is investigated in order to determine if the proposed controller guarantees a zero steady-state error.

For the DFIG connected DCMG system, the original harmonic components are generated from the stator voltage v_s . Substituting $s = \pm n\omega_s$ ($n=1, 2, \dots$) into the conventional controller (5-13), it can be found that $i_{s,dq}(n\omega_s) \neq 0$ if $v_{s,dq}(n\omega_s) \neq 0$. And it means that the stator current would be distorted when harmonic components are contained in the stator voltage.

Similarly, substituting $s = \pm n\omega_s$ ($n=1, 2, \dots$) into (5-16), when $Q=1$, it could be

observed that the frequency response of the closed-loop transfer function G_{i3} at the integral multiples of the fundamental frequency is equal to 0.

$$G_{i3}(s)\Big|_{s=\pm jn\omega_s}=0 \quad (n=1,2,\dots) \quad (5-19)$$

It indicates that the harmonic components with integral multiples of the fundamental frequencies in stator voltage will no longer distort the stator current in the proposed controller. The frequency responses of G_{i1} and G_{i2} at resonant frequency $s=\pm jn\omega_s$ ($n=1, 2, \dots$) are also obtained as given by (5-20) and (5-21).

Figure 5-8 Frequency response of RC loop

Figure 5-9 Frequency response of (a) G_{i1} , (b) G_{i2} and (c) G_{i3} with and without PIRC

$$G_{i1}(s)\Big|_{s=\pm jn\omega_s} = 0 \quad (n=1,2,\dots) \quad (5-20)$$

$$G_{i2}(s)\Big|_{s=\pm jn\omega_s} = 0 \quad (n=1,2,\dots) \quad (5-21)$$

If the stator voltage is distorted, harmonic components would be present in rotor current as well [19]. Thus, according to (5-20) and (5-21), the harmonic components of rotor current and disturbance signals with integral multiples of the fundamental frequency will not distort the stator current any more. And as a result, the harmonic components in stator current could be effectively eliminated.

Figure 5-8 shows the Bode diagram of RC loop shown in (5-11) with $Q=1$ and $k_{rc}=0.5$. The bandwidth of RC loop at each harmonic frequency is determined by k_{rc} while the gain of RC loop is governed by Q . It could be found according to Figure 5-8 that the RC loop has large gain at each harmonic frequency and it can eliminate multiple harmonics.

The frequency responses of G_{i1} , G_{i2} and G_{i3} are shown in Figure 5-9. It indicates that with the conventional controller, G_{i1} , G_{i2} and G_{i3} cannot eliminate the harmonic components but with PIRC, the effects of harmonic components in rotor current, disturbance signals and stator voltage could be damped.

5.4 Harmonic elimination of the stator power

As the stator of the DFIG is connected to the DCMG using an SSR, the output power of SSR could contain harmonics because of the uncontrollable rectifier. It is proposed in Section 5.3 that stator current is compensated by applying PIRC in RSC. However, the stator voltage is distorted. As a result, the output power of SSR contains large amount of harmonics. To compensate harmonics in the SSR output power,

Figure 5-10 Control of SC

BESS is found to be not a suitable candidate, as high frequency power components would be harmful for the batteries. Therefore, an SC interfaced with a DC-DC converter is proposed in this section for the DFIG output power harmonic elimination as shown in Figure 5-2. The most significant advantage SCs have over batteries is their ability to be charged and discharged continuously without degrading like batteries do. Therefore, SCs are more suitable for SSC output power harmonic mitigation. The control scheme of SC is shown in Figure 5-10. The SC is controlled to eliminate the harmonic components in i_{s-DC} to make the stator current flow to DCMG i_{s-DC1} a pure DC value.

In the SC controller, a PI control loop is applied in the control of the DC component and to keep the DC component of the current flow through SC to be zero. For harmonic elimination of the output power of SSR, a RC scheme is applied in the SC controller. As we assume the DC voltage of the DCMG is kept constant, i_{s-DC} is

linearly related to the output stator power. Thus, by eliminating the harmonic components of i_{s-DC} we can also eliminate the harmonics in the output stator power.

For harmonic elimination, the RC is applied in the SC controller as mentioned earlier. The RC scheme which presents large gains at the integral multiples of the fundamental frequency is proposed to overcome aforementioned drawbacks in PI and resonant controllers. The control scheme with RC loops of the DFIG is shown in Figure 4-10, where k_{rc} is the gain for RC loop, $G_f(s)$ is a phase lead compensator [19]. Thus, the transfer function of RC controller could be expressed as in (5-11).

In Figure 5-10, the output voltage of DC-DC converter is v_{SC} , suppose the voltage of DCMG is constant, so the current flow through the SC can be determined using

$$i_{SC} = \frac{v_{DC} - v_{SC}}{sL} \quad (5-22)$$

And the stator current flow of DFIG to the DCMG can be shown as follows.

$$i_{s-DC1} = i_{s-DC} + i_{SC} \quad (5-23)$$

In Figure 5-10, $i_{s-DC1-h}$ is the harmonic component of the SSR current on DC side.

The transfer functions of $i_{s-DC1-h}$ to harmonic reference of DCMG current $i_{s-DC1-h}^*$ and SSR current on DC side i_{s-DC} are given in (5-24)-(5-25), respectively.

$$G_{I1} = \frac{i_{s-DC1-h}}{i_{s-DC1-h}^*} = \frac{G_{RC}}{sL + G_{IPI} + G_{RC}} = \frac{k_{rc}G_f(s)H(s)e^{-sT}}{1 - (1 - k_{rc}G_f(s)H(s))e^{-sT}} \quad (5-24)$$

$$G_{I2} = \frac{i_{s-DC1-h}}{i_{s-DC}} = \frac{sL + G_{IPI}}{sL + G_{IPI} + G_{RC}} = \frac{(sL + G_{IPI}(s))(1 - e^{-sT})}{1 - (1 - k_{rc}G_f(s)H(s))e^{-sT}} \quad (5-25)$$

In (5-24) and (5-25), G_{lPI} is the transfer function of PI controller in Figure 5-10.

And

$$H(s) = \frac{1}{G_{lPI}(s) + sL} \quad (5-26)$$

Since $e^{-sT}(s = \pm n\omega_s, n = 1, 2, \dots) = 1$, one can get

$$G_{l1}(s = \pm n\omega_s, n = 1, 2, \dots) = 1 \quad (5-27)$$

$$G_{l2}(s = \pm n\omega_s, n = 1, 2, \dots) = 0 \quad (5-28)$$

(5-27) shows that harmonic components with integral multiples of the fundamental frequency of $i_{s-DC1-h}^*$ can be tracked. (5-28) indicates that harmonic components of i_{s-DC} can be eliminated. Therefore, the harmonic current flows to the DCMG from SSR can be effectively mitigated.

5.5 Voltage control of DCMG

5.5.1 Voltage regulation by control of BESS

The improved droop control method [35] is applied in the voltage control of the DCMG. The DC voltage of the microgrid is controlled by the local BESS. The control scheme of BESS is shown in Figure 5-11. The total load demand will be measured by the communications shown in Figure 5-11. The load sharing is decided by the capacity of each source. An ideal equitable load sharing is to generate an equal percentage of the rated power of each generator. In order to achieve an equitable load sharing and stable DC grid voltage, the improved droop control technique is applied in the control of BESS. Compared with the conventional droop control, the proposed

control method can prevent inequitable load sharing caused by uneven load distribution [35]. The local DC voltage error can also be reduced. The local DC voltage of x th node is controlled by BESS with the reference value determined in (5-29).

Figure 5-11 Control of BESS of x th node

$$v_{DC,x}^* = v_{DC}^0 - i_{source,x} d_x + \Delta v_{DC,x} \quad (5-29)$$

where the subscript x represents the value of x th node. v_{DC}^* and v_{DC}^0 are the reference and nominal DC voltage, respectively. d is the droop gain. And Δv_{DC} is the shift voltage which could be determined using

$$\Delta v_{DC,x} = k_x \bar{i}_{source} = \frac{k_x \sum_{x=1}^X i_{source,x}}{X} \quad (5-30)$$

where X is the number of nodes in the DCMG, k is the shift gain and $\bar{i}_{source}$ is the average load demand. With the shift voltage compensation, the distributed generator systems would be able to get an improved load sharing and more stable grid voltage.

The droop and shift gains need to be determined carefully to guarantee the stability and effectiveness of the controller and it has been discussed in [35].

In order to keep a high efficiency, the DFIG is controlled by RSC for MPPT in normal conditions. Therefore the output active power of the DFIG varies with the wind speed v_{wind} . However the capacity of the BESS is limited and the BESS can be fully charged due to long time charging. Therefore, the control mode needs to be changed due to different conditions. In mode 1, the BESS is controlled to regulate the local DC voltage as aforementioned. In mode 0, the output current of BESS is controlled to be zero. The mode selection will be discussed in the following sections.

5.5.2 Control of RSC

The control for RSC is given in Figure 5-12. In the DFIG control, the rotor current component is aligned along d-axis, denoted as $i_{r,d}$ and is regulated using the d-axis stator current. This is in order to force the fundamental reference frame to align itself with the vector of stator flux [77]. Thus,

$$i_{r,d} = -\frac{L_s}{L_m} i_{s,d} \quad (5-31)$$

Therefore, the d-axis stator current is related to stator reactive power Q_s . In the proposed configuration, $Q_s = 0$. Therefore, $i_{s,d}^* = 0$.

In normal condition, $i_{r,q}$ is controlled for MPPT as shown by mode 1 in Figure 5-12. However when the BESS is fully charged or cut off, $i_{r,q}$ is regulated for local DC voltage control with the reference DC voltage given in (5-29), as shown by mode 0 in Figure 5-12.

Figure 5-12 Voltage maintenance by control of RSC

5.5.3 Control mode selection

In order to improve the reliability of the system, different situations have been considered and accordingly, different control modes have been selected. As introduced previously, for control of BESS, mode 0 is to keep the output current of BESS to be zero and mode 1 is to regulate the local DC voltage to get an equal load sharing and stable DC voltage. For control of RSC, mode 0 is to obtain local DC voltage droop control by regulating the output power of DFIG and mode 1 is to obtain MPPT of DFIG.

In order to get a correct mode selection, the wind speed, state of charge (SOC) of BESS and the average load demand need to be known. Once the wind speed is known, the maximum output power can be determined using wind turbine characteristics stored in a lookup table. The maximum output current of DFIG $i_{DFIG,m}$ can be derived

Table 5-1 Mode selection of control of BESS and RSC

SOC of BESS	Wind condition	Control mode of BESS	Control mode of RSC
Fully charged	$i_{DFIG,m} > \bar{i}_{source}$	0	0
Fully charged	$i_{DFIG,m} \leq \bar{i}_{source}$	1	1
Normal	NA	1	1
Fully discharged	$i_{DFIG,m} \geq \bar{i}_{source}$	1	1
Fully discharged	$i_{DFIG,m} < \bar{i}_{source}$	0	0
BESS fault	NA	Cut off	0

as the grid voltage is constant. Then the mode selection can be done based on Table 5-1.

Table 5-1 shows that if the BESS is fully discharged and $i_{DFIG,m}$ is smaller than $\bar{i}_{source}$, the control of BESS and RSC is under mode 0. This situation should be avoided by design because this situation means that the power supply is not sufficient for long duration and some loads need to be cut off. If the BESS is fully charged and $i_{DFIG,m}$ is larger than $\bar{i}_{source}$, both the control of BESS and RSC should be under mode 0. In this condition, the DFIG cannot supply sufficient power for maintaining the local voltage thus the control of RSC should be under mode 1. If the BESS is out of service due to reasons like fault in BESS, the DFIG is controlled in mode 0. Otherwise, control mode 1 will be selected for control of both BESS and RSC.

5.6 Case study

In order to verify the effectiveness of the controllers, a simple DCMG system combined with four nodes is simulated using Matlab/Simulink. The DCMG system is shown in Figure 5-13. A local source consists of a DFIG and a BESS is connected at each node. The parameters of the system are given in Table 5-2.

Figure 5-13 Small DCMG for case study

Table 5-2 Parameters of the system

Parameters	Value
v_{DC}^0	250 V
z_{line}	$0.002\Omega, 0.001H$
Rated power of DFIG	7.5 kW
$i_{l2,1}, i_{l2,2}, i_{l3}, i_{l4,1}, i_{l4,2}$	25A
Frequency of DFIG	50 Hz

5.6.1 Harmonic elimination of stator current

A. Simulation Results

A DFIG with rated power of 1.5 MW is modeled using Matlab/Simulink. The parameters of the DFIG are shown in Table 4-1. V_{rated} is the stator side rated voltage.

- Case 1: Without harmonic compensator

In the simulations carried out, the DFIG is under conventional control before 2.7s. The waveforms of stator and rotor currents without harmonic compensator could be found from 2.5s to 2.7s in Figures 5-14 to 5-16 when the rotor speed is 0.8, 1.0 and 1.2 p.u., respectively. It could be found that when DFIG is connected to the DCMG, the stator current contains large harmonic components under conventional control in different rotor speed scenarios.

Figure 5-14 Waveforms of (a) stator voltage, (b) stator current, (c) rotor current, (d) FFT analysis of stator current at $\omega_r = 0.8$ p.u.

Figure 5-15 Waveforms of (a) stator voltage, (b) stator current, (c) rotor current, (d) FFT analysis of stator current at $\omega_r = 1.0$ p.u.

Figure 5-16 Waveforms of (a) stator voltage, (b) stator current, (c) rotor current, (d) FFT analysis of stator current $\omega_r = 1.2$ p.u.

- Case 2: With harmonic compensator

The PIRC scheme is applied after 2.7s in the simulations. It could be found from Figures 5-14 to 5-16 that after 2.7s when the PIRC is applied, the harmonic components in stator current are significantly reduced regardless of the rotor speed. Furthermore, it can be seen that from Figures. 5-14(c), 5-15(c) and 5-16(c) that compensation signals are added into the rotor current. The frequency spectrums of stator current have been shown in Figure 5-14(d), 5-15(d) and 5-16(d). According to the frequency spectrums, it can be found that the harmonic components can be effectively reduced by applying PIRC.

B. Experimental Results

Figure 5-17 Experimental setup

Figure 5-18 Experimental waveform of the stator voltage

A DFIG system connected with a DC source is constructed for experimental verification of the proposed methodology and the parameters of the system are listed in Table 4-1. The block diagram of the experimental system is shown in Figure 5-17. A DC machine is used to drive the rotor of the DFIG as a prime mover. The DC machine is controlled in torque producing mode, which simulates the wind turbine and gear box. The DCMG is emulated by two series connected DC sources. A resistive load is connected to the DCMG to consume the active power generated by the DFIG. The control system is implemented on a platform consisting of dSPACE 1104 and a programmable logical device.

Figure 5-18 shows the stator voltage of the DFIG. The stator voltage is distorted and the waveform matches the aforementioned analysis.

- Case 1: Without harmonic compensator

The stator and rotor currents under conventional control when the generator is in sub-synchronous ($\omega_r = 0.8$ p.u.), synchronous ($\omega_r = 1$ p.u.) and super-synchronous ($\omega_r = 1.2$ p.u.) conditions are shown in Figures 5-19(a), 5-20(a) and 5-21(a), respectively.

Figure 5-19 Experimental waveform of stator and rotor currents (a) without compensation, (b) with compensation at $\omega_r=1.0$ p.u.

Figure 5-20 Experimental waveform of stator and rotor currents (a) without compensation, (b) with compensation at $\omega_r=1.2$ p.u

Figure 5-21 Experimental waveform of stator and rotor currents (a) without compensation, (b) with compensation at $\omega_r=0.8$ p.u.

For the purpose of MPPT, the rotor speed of DFIG should be changed according to the wind speed. This experimental result shows that without the harmonic compensation control, large amount of harmonic components are present in the stator current which would degrade the efficiency and lifetime of the generator. Moreover, it can be found in the figures that the rotor current also contains harmonics even in the conventional control conditions.

- Case 2: With harmonic compensator

When PIRC is applied, the stator and rotor currents in different rotor speed conditions are shown in Figures 5-19(b), 5-20(b) and 5-21(b), respectively. Compared to Figures 5-19(a), 5-20(a) and 5-21(a), it could be found that the harmonic components of stator current are largely mitigated although the harmonics in rotor currents are not significantly increased. These experimental results verify that the proposed controller could eliminate the harmonics of the stator current effectively and the DFIG would be able to operate in DCMGs smoothly.

5.6.2 Harmonic elimination for the output power of DFIG

The effectiveness of control of SC is tested using simulation. Here it is assumed that the control of BESS and RSC are both under mode 1. The DC voltage is maintained at 250V which is constant and the wind speed and load demand are constant as well. The DFIG produces rated active power which is 7.5kW. The control of SC is shown in Figure 5-10. The simulation results of DC side SSR current and current of SC are shown in Figure 5-22. The control of SC starts working after 0.5s. Compared with the i_{s-DC1} without compensation in the first 0.5s, i_{s-DC1} with compensation contains 60% less harmonic components. Therefore, the power quality of the DFIG can be

significantly increased by reducing the harmonics of i_{s-DC1} . Moreover, it can be found that the SC absorbs harmonics from i_{s-DC1} and those harmonics are seen in i_{SC} when the compensation controller is applied.

Figure 5-22 Harmonic elimination of i_{s-DC1}

5.6.3 Load sharing under droop control with a step change load

The improved droop control is applied in the control of BESS in the DCMG system at each node. The performance of the proposed control scheme shown in Figure 5-11 is tested under simulation. In the simulation, S_1 is kept closed, S_2 is closed at 1s and open at 2s, S_4 is closed at 4s. The DC voltage and source current at each node are shown in Figure 5-23. The DC voltage waveforms show that the improved droop control scheme can keep the system stable and maintain the DC voltage constant during step load change conditions.

The step change of the source current at each node when S_1 is closed is very similar to that of S_2 . It means that the load location will not affect the equal load sharing in improved droop control too much and the errors are within an acceptable range.

When S_1 or S_2 is closed, very little differences could be found in the source current of each node. It indicates that the source location doesn't affect the equal power sharing too much as well. The simulation results verify that the improved droop control could be applied in this system to guarantee the equal load sharing and regulation of DC voltage.

Figure 5-23 Local DC voltage and source current at each node with step change load

5.6.4 Voltage regulation when BESS is out of service

When the BESS is fully charged or out of service due to faults for example, the control of RSC has to work in mode 0 to control the local DC voltage. Here suppose

Figure 5-24 Local DC voltage and source current at each node when S_I is open

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the BESS at node 1 is cut off at 1s by opening S_1 , while S_2 and S_4 are kept open. The current of DFIG in DC side, the current of BESS, the source current and DC voltage at each node are shown in Figure 5-24. Before the BESS is cut off, both the control of RSC and BESS are in mode 1 at each node. The DFIGs generate rated power before 1s which is larger than the load demand. Thus, the current of BESS is negative which means the excess active power of the generator charges BESS. When the BESS is cut off, $i_{B,1}$ becomes zero and if the control of RSC is kept in mode 1, the local DC voltage may increase due to the excess active power. According to Figure 5-24, it can be found that when the BESS is cut off and the control of RSC is switched to mode 0, $i_{DFIG,1}$ decreases and equal to $i_{source,1}$ to support the local DC voltage. And the operation of the other nodes will not be affected. As a result, the reliability of the DCMG system has been improved.

5.7 Conclusion

This chapter develops a novel connection scheme of DFIG connected in DCMG. In the proposed connection, an SSR is connected between the stator and the grid in order to reduce the cost of the DFIG. The harmonics in the stator current and output power caused by SSR can be significantly reduced by applying RC scheme in the control of RSC and SC so that the power quality of the system can be maintained. Moreover, in order to maintain the high efficiency of the DFIG, the control of RSC is designed for MPPT in normal operation and thus, the BESS is required to absorb or deliver active power when the power of DFIG is larger or smaller than the load demand respectively. For the purpose of increasing the reliability of the system, different modes of control of RSC and BESS have been developed, so that when the BESS is out of work or fully charged or discharged, the DFIG can be controlled for regulating the DC voltage

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and the system can be kept stable. Finally, the effectiveness of the proposed configuration and the corresponding controllers are verified by simulation results.

Chapter 6. Conclusion

6.1 Conclusion

This thesis concerns about the performance improvement of induction generator systems in wind power generation. In Chapter 1, the background of the research work and a brief introduction of the concerned issues are presented. The concerned issues include low voltage ride-through problem, harmonic compensation problem and the application in DC-microgrid of DFIG. The proposed solutions for such concerned problems are discussed in great detail in Chapter 3-5, respectively.

In Section 2.1, a brief literature review on LVRT of DFIG is given. Based on which, an improved MSDFIG is introduced for the purpose of improved LVRT in Chapter 3. The DF and the IG modes of operation of the DFIG are studied. Based on the equivalent circuits of the two modes, the transient currents when the DFIG switches from the DF to the IG and from the IG back to the DF modes are evaluated. The controllers of the GSC, RSC and crowbar in IG mode of connection are also described. In the IG mode of connection, both the active and reactive powers through the back-to-back converters can be controlled and in this manner, the converters can be prevented from over-loading. A suitable strategy to adjust the stator crowbar resistance of the MSDFIG has been developed. A method to re-synchronize and re-connect the DFIG to the grid has also been proposed. It is shown that the method can effectively reduce the transient currents when the DFIG reverts back to the DF mode from the IG mode. Simulation study shows promising results because the MSDFIG is demonstrated to be able to ride through grid fault much more effectively and perform much better than the conventional DFIG.

In Section 2.2, the harmonic elimination methods using APF, PI and PIR control are introduced. In order to keep the DFIG in low cost and improve the harmonic elimination performance, the harmonic problem of stand-alone DFIG is discussed and the RC is proposed for harmonic elimination of the stator voltage in Chapter 4. The stator voltage of the stand-alone DFIG may be distorted by non-linear or unbalanced loads. In order to prevent such voltage distortions and hence reduce their negative impacts, PIRC is proposed in this chapter for mitigating the levels of the voltage unbalance and harmonics. A single RC can compensate both the harmonic and negative sequence components which are integer multiples of the fundamental frequency, so the controller is structurally simpler compared to existing conventional control schemes which are developed in their respective harmonic reference frames. The superior performance of the proposed control scheme is verified by a series of simulation study and experimental tests.

Based on the literature review on DCMG-connected DFIG given in Section 2.3, in Chapter 5, a novel connection scheme of DFIG connected in DCMG is proposed. In the proposed connection, an SSC is connected between the stator and the grid in order to reduce the cost of the DFIG. The harmonics in the stator current and stator output power caused by SSC could be significantly reduced by applying RC in the regulation of RSC and SC respectively so that the power quality of the system can be improved. Furthermore, in order to maintain the high efficiency of the DFIG, the control of RSC is designed for MPPT in normal operation and thus, the BESS is required to absorb or generate active power when the power of DFIG is larger or smaller than the load demand. For the purpose of increasing the reliability of the system, different modes of the control of RSC and BESS have been developed. Therefore, when the BESS is fully charged or discharged, the DFIG can be controlled for the DC voltage regulation

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and the system can be kept stable. Finally, the effectiveness of the proposed configuration and the corresponding controllers are verified by simulation results.

6.2 Recommendations for Future Research

Notwithstanding of the above findings, the following areas are suggested for further investigations. These unresolved challenges are briefly discussed here to provide insights for future investigation. The potential research works will improve the performance of the scheme(s) proposed.

Mitigation of unbalanced and distorted stator voltage of stand-alone DFIG using RC is discussed in Chapter 4. RC is also applied in the stator current harmonic elimination of DCMG connected DFIG which is discussed in Chapter 5. Compared with the PI and PIR controller introduced in Section 2.2, RC technique for harmonic control is found having a lower calculation burden and a better performance in dealing with periodic signals. However, all the control methods dealing with harmonics are frequency-sensitive. When the DFIG is connected to a large grid where the frequency is considered to be constant, the harmonic elimination methods can achieve a great performance in harmonic mitigation. But the stand-alone DFIG or DCMG-connected DFIG of which the stator frequency is determined by the control of RSC, the stator frequency could have a small shift when a sudden change happens in the load side or generator side.

In PI or PIR control methods which are introduced in Section 2.2.3 and 2.2.4, respectively, the angle of Park's transformation will have an error if there is a frequency shift in the stator side. Besides, the frequency shift gets deteriorated in the harmonics because the error in the harmonic frequencies is multiples of that of the

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fundamental component. Therefore, the harmonic components in their corresponding reference frame will be no longer DC values and so that the PI and PIR controller will lose the effectiveness in the harmonic mitigation. According to the frequency response shown in Figure 4-9, the performance of PIRC will also be affected by frequency shift.

To solve the frequency shift problem, it is essential to track the fundamental frequency. Rather than using the fixed stator frequency, a possible solution for the frequency shift problem is the use of frequency adaptive control technique combined with the PIRC in the control of RSC. It is also presented by a few researchers [84, 85] that the frequency shift can be avoided by applying the RC in frequency domain. Therefore, the implementation of RC in frequency domain for DFIG harmonic elimination can be carried out in the future work.

The DCMG-connected DFIG is investigated in Chapter 5. It is proved by simulation and experimental results that the proposed control scheme of RSC can effectively reduce the harmonics in the stator current. However, the stator voltage is still distorted because of the use of SSR.

One possible path for stator voltage harmonic elimination is using a shunt compensation connected between the stator windings and the SSR. In order to improve the performance in harmonic elimination control, PIRC can be applied in the control of shunt compensation device. In such a scenario, the stator voltage can be purely sinusoidal while the cost of DFIG can be kept at a low value. However, the power rating of the converter and the capacitor of the shunt compensation should be carefully designed according to the magnitude of the harmonics.

The investigation on fault ride-through ability of the DCMG-connected DFIG is another concern in the DCMG-connected DFIG. In the grid-connected DFIG, it is required by the grid codes that the DFIG has to keep connected to the grid to generate reactive power. The DFIG has to ride through grid fault conditions due to the grid code requirement. However, as aforementioned, the fault ride through performance of DFIG requires improvement because of the low power rating of the converters. There are no such requirements for DCMG-connected DFIG because no reactive power is required in the DCMG so that it is possible to achieve a significant improvement in the performance of LVRT of the DCMG-connected DFIG. According to the configuration of distributed DFIG with power buffer and local loads shown in Figure 5-2, a possible solution for LVRT of DCMG-connected DFIG is to isolate the local sources and loads and design a stand-alone control scheme of the sources. Therefore, the inrush current caused by the grid fault could be avoided and both the sources and loads can ride through the grid fault smoothly. When the grid fault is cleared, it is proposed to reconnect the sources to the DCMG to support the active power as soon as possible. Therefore, the improvement of the fault ride through ability of the DFIG in DCMG can be seen as an interesting topic for DFIG in future work.

Appendix 3-A

The derivation of the expressions for the transient current is shown as follows. The following new symbols are defined:

$$\tau_s = \frac{L_s}{R_s}; \tau_r = \frac{L_r}{R_r}; \alpha = \frac{\tau_r}{\tau_s}; \sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (\text{A-1})$$

From (3-5), one can obtain the solution for the rotor current in the p domain as

$$i_{r,dq}(p) = \frac{\frac{1}{L_r} \left(\frac{1}{\tau_s} + j\omega_s + p \right) V_r + \frac{1}{L_s L_r} (j\omega_{sl} L_m + L_m p)}{\sigma p^3 + \left(\frac{1}{\tau_s} + \frac{1}{\tau_r} + j(\omega_s + \omega_{sl}) \sigma \right) p^2 + \left(\frac{1}{\tau_s \tau_r} - \omega_s \omega_{sl} \sigma + j\omega_s \frac{1}{\tau_r} + j\omega_{sl} \frac{1}{\tau_s} \right) p} \quad (\text{A-2})$$

Then the poles of (A-2) can be derived

$$\left. \begin{aligned} \xi_0 = p_0 &= 0 \\ \xi_{1,2} = p_{1,2} &= -\frac{1}{2\sigma\tau_r} (1 + \alpha) + j \left(\frac{\omega_r}{2} - \omega_s \right) \pm \frac{1}{2\sigma\tau_r} \sqrt{(1 + \alpha)^2 - 4\sigma\alpha - (\omega_r \sigma \tau_r)^2 + j2(\alpha - 1)\omega_r \sigma \tau_r} \end{aligned} \right\} \quad (\text{A-3})$$

Thus, the expression of rotor current in time domain is as given in (3-6). The constants in (3-6) are

$$\left. \begin{aligned} i_{r,dq}(\infty) &= C_0 \\ i_{r,dq}(0) &= C_0 + C_1 + C_2 \\ \frac{di_{r,dq}(0)}{dt} &= \xi_1 C_1 + \xi_2 C_2 \end{aligned} \right\} \quad (\text{A-4})$$

where $i_{r,dq}(\infty)$ is the steady state value of the rotor current in the IG mode. It can be derived using the following expressions

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$$\left. \begin{aligned} (R_s + j\omega_s L_s) i_{s,dq}(\infty) + j\omega_s L_m i_{r,dq}(\infty) &= 0 \\ (R_r + j(\omega_s - \omega_r) L_r) i_{r,dq}(\infty) + j(\omega_s - \omega_r) L_m i_{s,dq}(\infty) &= v_r \end{aligned} \right\} \quad (\text{A-5})$$

and one can obtain

$$\left. \begin{aligned} i_{r,dq}(\infty) &= \frac{Av_r}{B} \\ A &= R_s + j\omega_s L_s \\ B &= (R_s + j\omega_s L_s)(R_r + j(\omega_s - \omega_r) L_r) + \omega_s(\omega_s - \omega_r) L_m^2 \end{aligned} \right\} \quad (\text{A-6})$$

$di_{r,dq}(0)/dt$ is the initial differentiation value of rotor current and is governed by the expressions

$$\left. \begin{aligned} \left(R_s + j\omega_s L_s + \frac{d}{dt}\right) i_{s,dq}(0) + \left(j\omega_s L_m + \frac{d}{dt}\right) i_{r,dq}(0) &= 0 \\ \left(R_r + j(\omega_s - \omega_r) L_r + \frac{d}{dt}\right) i_{r,dq}(0) + \left(j(\omega_s - \omega_r) L_m + \frac{d}{dt}\right) i_{s,dq}(0) &= v_r \end{aligned} \right\} \quad (\text{A-7})$$

where

$$\frac{di_{r,dq}(0)}{dt} = \frac{1}{\sigma L_r} v_r + \left(\frac{L_m}{\sigma \tau_s L_r} + j \frac{\omega_r L_m}{\sigma L_r} \right) i_{s,dq}(0) + \left(-\frac{1}{\sigma \tau_r} + j \frac{-\sigma \omega_s + \omega_r}{\sigma} \right) i_{r,dq}(0) \quad (\text{A-8})$$

Appendix 3-B

With given initial conditions of ω_r , i_s and i_r , the transient rotor current can be readily determined by applying (3-7) – (3-10) to (3-6). In fact, once the initial steady-state active power delivered to the grid P_d and the pf are known, then the initial conditions can be derived as follows. The active power is given as

$$P_s = |V_s| |i_s| \cos \theta \quad (\text{B-1})$$

---

where it is assumed $v_s = 1 \angle 0^\circ$, and θ is the angle between v_s and i_s , P_s is the stator active power. Ignore the copper loss in the generator, one obtains

$$P_d = P_s - P_{sl} = (1-s)|v_s||i_s|\cos\theta \quad (\text{B-2})$$

In (B-1), P_d is the sum of stator and slip powers P_s and P_{sl} .

Under normal steady state conditions, the rotor speed of wind generator is controlled for MPPT. Take the GE 1.5 and 3.6 MW wind turbine-generators as examples, the MPPT curve is given as [86],

$$\omega_r = \begin{cases} -0.67P_d^2 + 1.42P_d + 0.51; & 0 \leq P_d < 0.75 \\ 1.2; & P_d \geq 0.75 \end{cases} \quad (\text{B-3})$$

Then the initial stator current is

$$|i_s(0)|\cos\theta = \begin{cases} \frac{P_g}{-0.67P_g^2 + 1.42P_g + 0.51}; & 0 \leq P_g < 0.75 \\ \frac{P_g}{1.2}; & P_g \geq 0.75 \end{cases} \quad (\text{B-4})$$

The reactive power capability of each GE 1.5 MW machine is +0.95/-0.90 pf, while for the 3.6 MW machine, it is +0.90/-0.90 pf [86]. With known pf, one can obtain the stator current using

$$i_s(0) = |i_s(0)|\cos\theta + j|i_s(0)|\sin\theta \quad (\text{B-5})$$

Whence the initial rotor current, rotor voltage are

$$i_r(0) = i_s(0) - \frac{v_s}{jX_m} \quad (\text{B-6})$$

$$v_r(0) = sv_s - si_s(0)[R_s + j(X_s - X_m)] + i_r(0)[R_r + js(X_r - X_m)] \quad (\text{B-7})$$

Appendix 4-A

According to (4-17), the Routh table is given in Table 3A-I.

Table 3A-I: Routh table of (3-17)	
$L_s L_r$	$L_s k_i$
$L_s R_r + L_s k_p + j\omega_{sl} L_s L_r$	0
$L_s k_i$	0

Whence, it can be established that if k_p and k_i are positive, the stability of the transfer function in (4-17) can be guaranteed.

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