SERIES VOLTAGE COMPENSATION FOR DOUBLY-FED INDUCTION GENERATOR WIND TURBINE LOW VOLTAGE RIDE-THROUGH SOLUTION

by

Omar Abdel-baqi

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Engineering

at

The University of Wisconsin-Milwaukee

August 2010
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Major Professor Date

Graduate School Approval Date
ABSTRACT

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The University of Wisconsin-Milwaukee, 2010
Under the Supervision of Adel Nasiri, PhD

Wind is clean and unlimited free source of energy. But in order for the wind energy to be effectively and efficiently harvest without interruption, the wind generators required to ride-through grid disturbances and support the grid during voltage sag events. The Doubly-Fed Induction Generator (DFIG) is known for its poor response to the voltage sags. This work develops an approach to provide a robust ride through technique for the DFIG during different types of voltage sags.

In this work, a mathematical model for the DFIG is developed and used to analyze the voltage sags effects. The DFIG stator flux is the main state that affects the system during the voltage sags. A component of the stator flux declines with the slow time constant of the generator during sudden voltage sag and forces a large rise of current in the rotor windings. This current rise damages double conversion power electronics converter connected to the rotor winding.
The existing techniques for Low Voltage Ride Through (LVRT) solutions have many drawbacks. In brief, they introduce undesirable spikes in generator torque and currents. In addition, they do not provide support to the grid during low voltage conditions.

In order to mitigate the effect of the slow declining component of the stator flux during voltage sags, the system is augmented with a series converter on stator circuitry. The converter injects a voltage on the stator to correct the air gap flux and to ultimately prevent the rotor current rise. A dead-beat control technique is developed to adjust the converter. In addition to the extensive computer simulation, a laboratory scale prototype is developed to validate the proposed solution. The size of the energy storage system required for the converter is also discussed in this thesis.

Future work directions are proposed including more robust control technique, minimizing number of additional parts and bigger laboratory scale prototype.
In memory of my parents,
with love and gratitude.

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NOMENCLATURE

Acronyms and Abbreviations

AWEA American Wind Energy Association
DFIG Doubly Fed Induction Generator
FERC Federal Energy Regulatory Commission
FOC Field Oriented Control
GSC Grid Side Converter
FRT Fault Ride Through
IGBT Insulated Gate Bipolar Transistor
MSC Rotor Side Converter
NERC National Energy Regulatory Commission
PCC Point of Common Coupling
PM Permanent Magnet
PMSG Permanent Magnet Synchronous Generator
pu Per Unit
PWM  Pulse Width Modulation
SCR  Silicon Controlled Rectifier (Thyristor)
SCIG  Squirrel Cage Induction Generator
SG  Synchronous Generator
SGSC  Series Grid Side Converter
TSR  Tip Speed Ratio (\(\lambda\))
LVRT  Low Voltage Ride Through

Symbols

\[ j = \sqrt{-1} \]
- Space vector dot product
- Space vector cross product
* Complex conjugate

\[ \Re \]  Real part
\[ \Im \]  Imaginary part
\[ t \]  Time
\[ \omega \]  Speed or frequency
\[ s \]  Slip/Second
\[ L \]  Inductance
\[ R \]  Resistance
\[ C \]  Capacitance
\[ C_p \]  Coefficient of performance
\[ J \]  Rotational inertia
\[ v \]  Voltage
\[ i \]  Current
\[ \psi \]  Flux
\[ T \]  Torque
\[ \tau \]  Time constant
\[ P \]  Pole pairs or Power
\[ Q \]  Reactive power
\[ N \]  Turns ratio or Per Unit Characteristic Voltage
\[ \rho \]  Density of air
\[ V \]  Wind speed
\[ A \]  Area
\[ \lambda \]  Tip speed ratio
\[ \beta \]  Blade pitch angle

Subscripts

\[ m \]  Mechanical
\[ w \]  Wind
\[ s \]  Stator
$r$ Rotor circuit (T-model), or Rotor speed (for $\omega$)
$R$ Rotor circuit (Γ-model)
$e$ Electrical
$s$ Slip
$dc$ Direct current
$q$ q-component
$d$ d-component

**Superscripts**

$S$ Stationary (or stator) reference frame
$r$ Rotating (or rotor) reference frame

**Additional Notation**

$\rightarrow$ Space vector quantity
$\sim$ Phasor quantity


**Introduction**

Currently, the majority of electricity is produced from coal, nuclear power, natural gas, hydropower, and petroleum. Fossil fuels such as coal, natural gas, and petroleum have limited supply and create undesirable effects on the environment. For instance, global warming or climate change has been directly linked to the use of fossil fuels. On the national level, it has increased our dependence on foreign oil and compromised our national security. These problems can be alleviated by significantly increasing the percentage of renewable fuel source from its current 2.3% of total electric power production.

The major challenge is how to integrate this intermittent, uncertain, and non-dispatchable wind power into the power grid. In addition to issues mentioned above, Federal Energy Regulatory Commission (FERC) accepted a joint recommendation by American Wind Energy Association (AWEA) and North American Electric Reliability Corporation (NERC) to impose a new regulation on electric utilities regarding wind turbine Low Voltage Ride Through (LVRT) [3]. Due to increasing penetration of wind energy, this regulation requires that the wind turbines, the same as conventional generators, stay online and support the grid with reactive power during short circuit. In addition, they should resume providing active power as soon as the line voltage is built up. According to the new regulation, the machine has to remain online if a three-phase short circuit fault occurs at its terminal and lasts for 0.15 second followed by a ramp voltage rebuild to 90% of nominal voltage in 2.85 seconds. The requirements concerning immunity to voltage dips as prescribed by AWEA and FERC is shown in Figure 1-1.
The wind turbine generator may disconnect from the line transiently but must reconnect within 2 seconds and rebuild power output at 20% of rated power per second. This new regulation has been a challenging requirement for the wind turbine manufacturers and utilities to meet. Newer types of wind turbine generators are more susceptible to short circuit fault due to presence of power electronics components. Many companies and research institutions are working on developing LVRT techniques for these generators.

In the early stage of wind turbine development, fixed-speed Induction Generators (IG) were used. These types of machines require reactive power compensation. In addition, they cannot provide power at low wind speed and cannot capture the maximum power out of wind. The trends for wind power generators have been shifted from fixed speed generators to variable speed generators such as Doubly-Fed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG). DFIGs offer some
advantages over the simple IGs including controllable reactive power output, higher energy capture, machine speed and torque control capability. They have become the main type of generator for wind turbine applications [3]. They use a back-to-back converter on the rotor to inject variable frequency current into the rotor. The converter is rated at about 20%-30% of the nominal power of the machine. The presence of this converter makes this machine more vulnerable to short circuit faults. When the fault occurs on the grid side, the stator current rises, this rising of stator currents result in flux increase in the rotor winding and, consequently, current increase in the rotor. If this current is not controlled or bypassed from the back-to-back converter, it will damage the switches.

Among all the issues mentioned above, LVRT and wind power fluctuations are the major obstacles for integration of wind energy in the grid. Existing wind forecasting methods can provide accurate average wind power projection using physical and statistical data [4]. If a viable method is used to remove the wind power variation and to provide average energy, wind energy can be treated as conventional generators in the grid.

Thus the focus of this work is on the use of a series connected inverter to enable the DFIG wind turbines to ride through severe voltage sags. The capabilities and limitations of this new topology are evaluated through analysis of steady state and dynamic properties, simulation and laboratory hardware demonstration.
Chapter 1 Wind Turbine for Utility Application

1.1 Wind Energy History

The first practical windmills were built in Sistan, a region between Iran and Afghanistan, since at least the 9th century, or possibly earlier in the 7th century. These were vertical-axle windmills, which had long vertical drive shafts with rectangle shaped blades. Made of six to twelve sails covered in reed matting or cloth material, these windmills were used to grind corn and pump water, and were used in the grist milling and sugarcane industries. Windmills were in widespread use across the Middle East and Central Asia, and later spread to China and India from there. Horizontal-axle windmills were later used extensively in Northwestern Europe to grind flour beginning in the 1180s, and many Dutch horizontal-axle windmills still exist. By 1000 AD, windmills were used to pump seawater for salt-making in China and Sicily [2].

Getting a fresh breeze in its sails from economic recovery legislation passed in early 2009 by Congress, the U.S. wind industry broke all previous records by installing over 10,000 megawatts (MW) of new generating capacity (enough to serve over 2.4 million homes) during the year, setting the stage for a strong 2010 if Congress and the Administration enact key policies to continue accelerated growth across the entire renewable energy sector [1]. Figure 1-2 shows the exponentially increasing rate of wind turbine insulation in United State between years of 2001 and 2009.
LONG-TERM POLICY NEEDED: A national Renewable Electricity Standard (RES) is needed to create a stable, U.S-wide market for capital investment.

Figure 1-2. Annual insulation U.S. wind power capacity [1].

The centerpiece of the recovery legislation for wind was a provision allowing wind farm developers to receive a direct payment from the U.S. Treasury, rather than the previously existing Production Tax Credit (PTC). Under this provision, the Treasury provided more than $1.5 billion in 2009 in crucial capital to at least 37 different wind projects, using large and small turbines, powering the equivalent of 800,000 homes and providing a lifeline for the industry. Even more importantly, 40,000 jobs were saved [1].

While 2009’s manufacturing slowdown was bad news, the good news is that a solution is readily available: a strong national Renewable Electricity Standard (RES) with aggressive and binding near- and long-term targets which will create the market certainty that
manufacturers need in order to invest, enabling the U.S. to become a wind turbine manufacturing powerhouse [1].

New Announced Facilities
- Daneket Corporation (generators)
- Dragon Wind
- United S. (towers)
- Solaq North American LLC
- Ameren A (sensors and blades)
- Mariner Power
- Mariner M (turbines)
- Nordic WindPower
- Saco, ME (turbines)
- RBC Bearings Inc.
- Hudson, KY bearings
- Tower Tech Systems
- American TK (towers)
- Vacon Inc.
- Chippington, MA (towers)
- Vestas
- Boston, MA (towers)
- Winergy
- Sint (turbines)

New Announced Facilities
- Aeronautica Windpower/Goodyear International
- Durham, NH (turbines)
- Bach Composite Industry
- Fortuna, CO (laminates)
- Continental Wind Power
- Santa Paula, CA (turbines)
- Creative Foam Corp.
- Longmont, CO (laminate)
- EMA Electromecanica
- Swindale, TX (electric components)
- Energy Composite Corp.
- Wickenburg, AZ (electric components)
- GE
- Dorow MI (RSC rachis)
- Mitsubishi
- Fort Collins, CO (turbines)
- PMC Technology
- Golden, CO (laminates components)
- Powin
- Tualatin, OR (laminate)
- SGS USA
- Wheeling, ID (electric components)
- Siemens
- Austin, TX (turbines)
- BUR Energy
- Oak Creek, OH (turbines)
- Tindall
- Warren, KS (poles)
- VENT Energy
- Knowsley, UK (turbines)
- Ventower
- Monroe, MI (poles)
- Windermere
- New Albany, IN (turbines)
- Windronics
- Madera, CA (turbines)
- Wind Tower Systems
- Oswego, NY (poles)
- Zarago Aluminum Systems
- Arturo, TX (turbines)

Figure 1-3. Facilities opened or expanded in 2009 [1].
With a total of more than 35,000 MW of wind generation operating at the end of 2009, the U.S. today has more wind capacity installed than any other country. The location of the opened or expanded facilities in USA in 2009 is shown in Figure 1-3. Yet a closer look at the numbers gives a different picture. In 2009, the U.S. installed more wind capacity (10,010 MW) than it ever had before, but trailed both Europe (10,500 MW) and China (13,800 MW). With this large number of wind turbines installed the number of wind industry job saved in 2009 in USA is significant, as can be seen in Figure 1-4.

State-by-state, as can be seen in Figure 1-5, the U.S. continued to see strong growth in Texas and the Northwest. One up-and-coming area of growth in 2009 was the Midwest states of Indiana and Illinois. Texas again installed the largest amount of new capacity, driving it past the 9,000-MW mark in total installations. Iowa now has a total of 3,670 MW installed, consolidating its position as #2, behind Texas and ahead of California. With several large wind farms added, Washington and Oregon pulled ahead of Minnesota to round out the top five states.
1.2 Modern Wind Turbines

1.2.1 Wind Turbine Components

Wind turbines convert the kinetic energy of the wind into electrical energy. This is typically realized with several blades or airfoils attached to a shaft which rotates due to the pressure exerted by the wind. The rotating shaft drives the rotor of an electric generator. Either a gearbox or a high pole count generator is used to increase the relatively slow rotor speed for compatibility with the grid electrical frequency. Variations in electrical architectures employ a full or partial power handing power electronics interface with the grid. An illustration of the power processing path in a utility connected wind turbine is presented in Figure 1-6.
The components in the power train are controlled to achieve three principal objectives: 1. extract the maximum possible energy from the wind; 2. protect the wind turbine from damage; 3. satisfy grid connection requirements. Maximizing energy extraction is non-trivial; the energy that can be extracted from the wind is a nonlinear function of the rotor speed, wind speed, and blade pitch. The components of a utility scale wind turbine can be easily damaged by high winds, or sudden wind gusts. At particular risk are the gearbox and power converters, each of which are described in detail in the state of the art review of wind turbine architectures. Grid connection requirements specify power quality, reactive power support, and grid disturbance ride through, among others.

The major components and properties of a modern utility-scale horizontal-axis wind turbine are identified in Figure 1-7.
1.2.2 Wind Energy Extraction

Wind turbines convert the kinetic energy of the wind into electrical energy. The amount of kinetic energy related power in the wind, $P_w$, is proportional to the wind density $\rho$, area through which it passes, $A_b$, the coefficient of performance $C_p$, and wind speed, $v_w$, cubed, as expressed in
The coefficient of performance, $C_p$, itself is not a constant for a given airfoil, but rather is dependent on a parameter $\lambda$, called the tip-speed ratio, which is the ratio of the speed of the tip of the blade to the speed of the moving air stream. Figure 1-8 shows $C_p$ as a function of $\lambda$ for a modern wind turbine. Blade pitch adjustment allows the energy capture to be optimized over a wide range of wind speeds (even if the rotational speed of the shaft is relatively constant), while still providing for over-speed protection through large adjustments in pitch angle.

Figure 1-8. Coefficient of performance ($C_p$) vs. tip speed ratio ($\lambda$) for various blade pitch angle ($\beta$) for modern wind turbine [6].
The mechanical power, $P_m$, extracted from the wind can then be expressed as

$$P_m = \frac{1}{2} \cdot \rho \cdot A_h \cdot v_r^3 \cdot C_p(\lambda, \beta) = C_p(\lambda, \beta)P_w$$

(1-2)

The rotor pitch angle refers to the angle of the rotor blade with respect to the plane of blade rotation, as shown in Figure 1-9.

![Blade Cross Section](image)

Figure 1-9. Rotor blade pitch. ($R_b =$ blade radius, $v_{rel} =$ relative wind speed, $\beta = $ rotor pitch angle, $\alpha =$ aerodynamic angle of attach)[7].

A contour plot of the extracted mechanical power vs. wind speed and rotor speed for a typical wind turbine is presented in Figure 1-10.
1.3 Wind Turbine Types

In the early stage of wind turbine development, fixed-speed Induction Generators (IG) were used. These types of machines require reactive power compensation. In addition, they cannot provide power at low wind speed and cannot capture the maximum power out of wind. The trends for wind power generators have been shifted from fixed speed generators to variable speed generators such as Doubly-Fed Induction Generators (DFIM) and Permanent Magnet Synchronous Generators (PMSG). DFIGs offer some advantages over the simple IGs including controllable reactive power output, higher energy capture, machine speed and torque control capability. They have become the main
type of generator for wind turbine applications [3]. They use a back-to-back converter on
the rotor to inject variable frequency current into the rotor. The converter is rated at about
20%-30% of the nominal power of the machine. The presence of this converter makes
this machine more vulnerable to short circuit faults. When the fault occurs on the grid
side, the stator current rises, this rising of stator currents result in flux increase in the
rotor winding and, consequently, current increase in the rotor. If this current is not
controlled or bypassed from the back-to-back converter, it will damage the switches.

Among all the issues mentioned above, LVRT and wind power fluctuations are the
major obstacles for integration of wind energy in the grid. Existing wind forecasting
methods can provide accurate average wind power projection using physical and
statistical data [4]. If a viable method is used to remove the wind power variation and to
provide average energy, wind energy can be treated as conventional generators in the
grid.

1.3.1 Fixed-Speed Wind Turbine with squirrel Gage Induction generator

Historically, the most common type of utility connected wind turbine has been the
fixed speed squirrel cage induction generator (SCIG) based machine, as shown in Figure
1-11. This topology is often referred to as the “Danish concept”, and is known for being
simple and reliable, but also producing low power quality and being generally
unpalatable to utility system operators [3,4].
In this architecture, the turbine rotor shaft is connected to the generator rotor via a fixed ratio gearbox. The turbine blade pitch angle is held constant for all wind speeds. Due to the line connection of the machine and small slip range, the rotor speed is nearly constant at all wind speeds. Consequently, aerodynamic energy capture is below maximum at all wind speeds outside of a narrow range near the optimal tip speed ratio. Above rated wind speed, the air flow around the blades begins aerodynamic stall. Aerodynamic stall is characterized by separation of the flow region from the top of the blade, resulting in a reduction of lift [3,4].

Electrically, the power flow path is simple as well. The stator of the induction generator is connected to the grid via a step-up transformer. The reactive power needs of the induction generator are typically met with local reactive power compensation, typically in the form of a switched capacitor bank. This can be problematic due to the associated voltage surges at the PCC and torque spikes on the gearbox. Wind gusts can also result in high transient shaft torque due to the stiff torque – speed curve of a low slip induction generator and lack of blade pitch control [3]. The gusts also result in power surges and poor power quality at the PCC [8].
Generators with large rated slip are more mechanically compliant and have a slightly wider range of rotor speeds for optimum aerodynamic energy capture. Unfortunately, these machines also have increased electrical losses, and lower electrical efficiency [3]. Voltage fluctuations in the 1 to 10 Hz range due to blade-tower wind shadow and electrical resonances can produce visually disturbing flicker in lighting elements electrically local to wind farms [9,10]. The reactive power requirements and power quality issues are often compromised by the fact that wind turbines are often installed in electrically remote locations with low short circuit current ratios [11]. The line connected induction generator is very susceptible to grid voltage sags and swells. SCIG based wind turbines must be disconnected from the grid in the event of a voltage sag in order to protect the gearbox and blades from torque spikes. Subsequent resynchronization can also be problematic [11,12].

1.3.2 Variable Speed Permanent Magnet Synchronous Generator

An alternative to directly connected SGIG wind turbine is the direct drive permanent magnet synchronous generator (PMSG) topology presented in Figure 1-12.

![Figure 1-12. Variable speed permanent magnet synchronous generator (PMSG) wind turbine.](image)
The direct drive PMSG architecture is capable of full variable speed operation by virtue of full power handling back to back VSCs. Each of the VSCs consists of three pulse width modulated (PWM) IGBT-diode based phase legs [13]. The rotor speed is varied for optimum tip speed ratio operation and the rotor blades are feathered to throttle the aerodynamically generated shaft torque at high wind speeds. In lieu of the gearbox, a high pole count generator provides the conversion of the low rotor shaft speed to a modestly high electrical frequency for compatibility with the machine side VSC.

The machine side converter extracts power from the PMSG by control of the magnitude and phase of the voltage applied to the machine’s stator terminals. The dc bus of the machine side converter is connected to a second VSC on the grid side. The back to back VSCs and filter components must be rated to handle the full turbine power. This arrangement has higher losses in the converters [8]. These added losses are approximately offset by the efficiency gains due to the elimination of the gearbox [14].

Elimination of the gearbox has added benefit of increased turbine reliability and reduced maintenance costs. This architecture has also been shown to comfortably ride through grid voltage dips down to 0.15 pu [15]. However, the PMSG WT has seen very limited commercial development due to the high capital costs associated with the high pole count permanent magnet generator and full rated power converters.
1.3.3 Variable Resistance Wound Rotor Induction Generator

This type of wind turbine generator is similar to the induction generator except the cage rotor is replaced by a wound rotor. The rotor is connected to external components through the use of slip rings. The external components are a rectifier and a resistor as shown in Figure 1-13 below.

Figure 1-13. Variable Resistance Wound Rotor Induction Generator Wind Turbine. The purpose of the external resistance is to adjust the slip of the generator. The advantage is that it increases the speed range of the generator from 1-2% over synchronous speed, as in the induction generator, to up to 10% over synchronous speed. This type of generator has the disadvantages of the induction generator mentioned above plus the reliability issues of the added slip rings.

![Variable speed permanent magnet synchronous generator (PMSG) Wind turbine.](image)

1.3.4 Variable-Speed Wind Turbine with Double Fed Induction Generator

Several of the limitations associated with the SCIG and high costs of the PMSG can be overcome with the doubly feed induction generator (DFIG) system presented in Figure 1-14. This architecture is the most common for utility scale wind turbines.
The DFIG topology is capable of limited variable speed operation via a pair of back to back VSCs between the rotor circuit and the PCC. Each of the VSCs typically consists of three pulse width modulated (PWM) IGBT-diode based phase legs.

The rotor circuit of the DFIG is accessed via slip rings for connection to a voltage source converter (VSC), which is commonly referred to as the machine side converter (MSC). The stator circuit of the machine is connected to the grid via a step-up transformer, but without a power converter interface. The dc bus of the MSC feeds a VSC connected in parallel with the stator coils, commonly called the grid side converter (GSC) [4].

The rotor speed is varied for optimum tip speed ratio operation across a wide wind speed range. The rotor blades are feathered to throttle the aerodynamically generated shaft torque at high wind speeds. The low turbine rotor speed is geared up to a high generator shaft speed with a fixed ratio gearbox [4,16].

Figure 1-14. Variable speed doubly fed induction generator wind turbine.
The classical DFIG based wind turbine does not fare particularly well during sag events. Typically the current on the rotor inverter exceeds its rated value during extreme voltage sags. These limitations are discussed more in depth in Chapter 4. Nonetheless, the challenge posed by low voltage ride through requirements is problematic for DFIG wind turbine manufacturers, and forms the motivation for the present work.
Chapter 2 Grid Faults

As the penetration of wind energy into the grid has increased, system operators and regulatory bodies have increasingly required wind turbines to provide many of the ancillary services previously only demanded of conventional generators. The asynchronous generators and power electronics interfaces typical of conventional wind power plants have different capabilities from conventional synchronous generators. As wind penetration has grown, these differences have had an increased impact on the ability of system operators to maintain grid stability, particularly during disturbances or faults. Traditional grid connection requirements focused on protection of the wind turbine itself.

2.1 Grid Connection Requirements under Normal Operating

Present grid connection codes include wind turbine requirements for both nominal and faults conditions on the grid. Almost all connection codes require provision of either a voltage-droop characteristic or a specific reactive power range, an example of which is shown in Figure 2-1. These requirements are not particularly challenging and can be addressed in a number of ways including: discretely switched compensation; static VAR compensators (SVC); and static synchronous compensators (STATCOM); or a combination thereof. In the case of DFIG and wind turbines with back-to-back voltage source converters, the phase of the output current can be controlled directly, within converter ratings. In addition, power-frequency operating ranges are also specified for wind turbines during nominal (un-faulted) grid conditions [17,18,19,20]. One example of such a power-frequency droop curve is shown in Figure 2-2.
Figure 2-1. Power factor (reactive power) range requirements for: E.ON (a TSO of Germany); Scottish (Scotland), ELTRA (a TSO of Denmark), ESBNG (Ireland) [26].

Figure 2-2. Available power vs. frequency droop curve for Ireland (50 Hz nominal) [21].

### 2.2 Recent Grid Codes

**Europe:** The grid codes of Europe are affected by the fact that the grid has traditionally been strong and stable – but the fact that the wind power penetration has been increasing - LVRT (Low Voltage Ride Through) has entered the scene and most grid codes at least specifies LVRT requirements as defined by the German E.ON. In Spain, Scotland and Ireland the grid codes exceeds the “standard” requirements [55][56][57].
**Australia & New Zealand:** Are characterised by a weak and unstable grid with frequency variations from -10 % to +6 % (in extreme) and -6 % to +4 % (more common). Voltage control and site dependent requirements are standard [55][56][57].

**North America:** Characterised by a large number of “smaller” power systems requiring local control capabilities such as voltage control. The PF range is more standardized as 0.9c to 0.9i [55][56][57].

### 2.2.1 Grid Codes Trends

**Voltage control:** Future demands is going towards operation in a voltage set point control mode; with a continuously-variable, continuously-acting, closed loop control voltage regulation system, acting like a synchronous generator, where reactive power changes are based on measured voltage [55][56][57].

**Power control:** The trend in power control is fast ramp rates – both up and down, in order to support the frequency of the grid. The latest comments for GB grid codes for power recovery after grid faults states power restoration of 90% within 1s. Further frequency control is required in some countries, both under frequency and over frequency support [55][56][57].

**Plant control:** Having wind power plants tending the capabilities of primary control units, traditional power system control features are indisputable. As the need for more
dynamical response will increase, the needs for fast and reliable control-infrastructure between the turbines in a park facility are increasing [55][56][57].

**Low voltage ride-through:** Is becoming standard for all grid codes! In addition to symmetrical faults, which are three-phased, new trend setting grid requirements will be covering single and two-phase faults ride-through capability. Voltage support during grid disturbances is becoming a common requirement. An increase in the low voltage duration is foreseen – today GB codes mention 3 min. at 85 % voltage [55][56][57].

**Simulation models:** Validated park control models with full disclosure are already defined for various grid code drafts. Park simulation models are an integrated part of the tender phase in more and more projects. Most connection agreements are decided on background of simulation studies. Also non-confidential block diagrams are required, mainly Australia and New Zeeland, but US are also requiring open-source models. PSCAD, DigSilent and PSS/E are preferred tools [55][56][57].

### 2.3 Types of Voltage Sags

Voltage sags occur principally due to faults on the power line, caused primarily by lightning strikes, wind & tree contacts, ice, earthquakes, fire, explosions, falling trees, flying objects, animals, and contamination [21]. The fault current can produce a voltage sag over a wide area of the network. Voltage recovery occurs when the fault is either isolated by breakers or clears itself [23,24]. If breakers clear the fault, voltage recovery
takes place in stages and depends on the type of fault [33]. The percent of each fault type by occurrence is presented in Table 2-1.

<table>
<thead>
<tr>
<th>Fault Type</th>
<th>% of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Phase-to-Ground (φn)</td>
<td>70 – 85</td>
</tr>
<tr>
<td>Phase-to-Phase (φφ)</td>
<td>8-15</td>
</tr>
<tr>
<td>Phase-to-Phase-to-Ground (2φn)</td>
<td>4-10</td>
</tr>
<tr>
<td>Three-Phase-to-Ground (3φ)</td>
<td>3-5</td>
</tr>
</tbody>
</table>

The voltage seen at the terminals of the wind turbine depends on several factors, including the equivalent Thevenin network model, fault location, type, and impedance, and properties of the interface transformer. For balanced (3φ) faults, a voltage divider model is commonly used for determining the fault voltage during a sag event, as shown in Figure 2-3 [23,24]. In this model the contribution of the wind turbine current to the PCC voltage is typically neglected both before and during the sag event [23,24].

\[
V_{\text{pcc}} = E \frac{Z_f}{Z_f + Z_s} \quad (2-1)
\]

Figure 2-3. Voltage divider model commonly used for determining sag voltage for balanced faults [23,24].
The angle of the PCC voltage phase during sag is determined by the X/R ratio of both the fault and source impedances. If the fault X/R ratio is different from the source, there will be a “phase angle jump” in at the voltage phasors at the start of the sag event. For large wind farms connected to transmission grids, consistent X/R impedance ratios in the transmission lines do not typically result in phase angle jumps.

For unbalanced faults, the method of symmetrical components must be used to determine the remaining phase voltages [21,25]. The four different types of faults noted in Table 2-1 produce different voltage phasor responses at the wind turbine terminals, depending on the nature of the transformer connections between the fault and the wind turbine [23,25]. An illustration of the typical wind turbine transformer connections and a table of the corresponding sag type seen in Figure 2-4. It should be noted that for a fault at the PCC, this configuration of transformer results in only four types of voltage sags at the terminals of the DFIG wind turbine, namely A, C, D & G. It can be seen from Figure 2-4 that a ΔY transformer will convert between sag types C & D, and F & G.
Figure 2-4. Common transformer connections for wind turbine and the types of phase-neutral voltage sags (dips) seen for a given fault at the PCC and bus location [23,25]

A table of the voltage phasors for the different sag types is presented in Table 2-2.

The derivation of the sag phasor voltages in Table 2-2 assumes that positive, negative and zero sequence impedances are equivalent. When studying the effect of voltage sags on wind turbines, it is sufficient to know the sag type and value of the characteristic voltage, $V$ [32]. The per unit characteristic voltage is defined as

$$h = \frac{V}{V_{nor}}$$  \hspace{1cm} (2-2)

As mentioned previously, large wind farms connected to transmission grids, consistent X/R impedance ratios in the transmission system do not typically result in phase angle jumps. As a result, $h$ will typically be a real valued.
Table 2-2. Sag types and the corresponding per unit phase voltages as a function of per unit characteristic fault voltage, $h$ [23,25].

<table>
<thead>
<tr>
<th>Sag Type</th>
<th>$V_a$</th>
<th>$V_b$</th>
<th>$V_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$h$</td>
<td>$-\frac{1}{2} h - \frac{1}{2} jh\sqrt{3}$</td>
<td>$-\frac{1}{2} h + \frac{1}{2} jh\sqrt{3}$</td>
</tr>
<tr>
<td>B</td>
<td>$h$</td>
<td>$-\frac{1}{2} - \frac{1}{2} j\sqrt{3}$</td>
<td>$-\frac{1}{2} - \frac{1}{2} j\sqrt{3}$</td>
</tr>
<tr>
<td>C</td>
<td>$1$</td>
<td>$-\frac{1}{2} - \frac{1}{2} j\sqrt{3}$</td>
<td>$-\frac{1}{2} + \frac{1}{2} j\sqrt{3}$</td>
</tr>
<tr>
<td>D</td>
<td>$h$</td>
<td>$-\frac{1}{2} h - \frac{1}{2} j\sqrt{3}$</td>
<td>$-\frac{1}{2} h + \frac{1}{2} j\sqrt{3}$</td>
</tr>
<tr>
<td>E</td>
<td>$1$</td>
<td>$-\frac{1}{2} h - \frac{1}{2} j\sqrt{3}$</td>
<td>$-\frac{1}{2} h + \frac{1}{2} j\sqrt{3}$</td>
</tr>
<tr>
<td>F</td>
<td>$h$</td>
<td>$-\frac{1}{2} h - (\frac{1}{3} + \frac{1}{6} h) j\sqrt{3}$</td>
<td>$-\frac{1}{2} h + (\frac{1}{3} + \frac{1}{6} h) j\sqrt{3}$</td>
</tr>
<tr>
<td>G</td>
<td>$\frac{1}{3}(1+2h)$</td>
<td>$-\frac{1}{3} - \frac{1}{2} h - \frac{1}{2} jh\sqrt{3}$</td>
<td>$-\frac{1}{3} - \frac{1}{2} h + \frac{1}{2} jh\sqrt{3}$</td>
</tr>
</tbody>
</table>

For all fault types the characteristic per unit voltage is assumed to correspond directly to the voltage envelopes of the grid code ride through requirements (i.e $h = 0.15$ corresponds to a sag down to 15% voltage remaining between either the smallest two phases or phase to neutral). A plot of the time domain phase voltages and stationary and synchronous frame space vectors are presented in Figure 2-5 and Figure 2-6 respectively. Sag types B, E & F are omitted from the figure since they are not typically seen at DFIG wind turbine terminals.
Figure 2-5. Sag phasors and waveforms for characteristic remaining voltage of $h = 0.5$: abc phase voltages.

Figure 2-6. Sag phasors and waveforms for characteristic remaining voltage of $h = 0.5$: stationary and synchronous frame space vectors.
2.4 Ride-Through Properties

The various constraints acting on the design and interconnection of utility scale wind turbines yields the following set of desirable properties for any voltage sag ride through solution. These properties are summarized in Table 2-3 and described below.

Table 2-3. Summary of Desirable Ride-Through Properties

<table>
<thead>
<tr>
<th>Turbine Protection</th>
<th>Converter Device Voltage</th>
<th>Converter Device Current</th>
<th>Grid Connection</th>
<th>Sag Types</th>
<th>Grid Current</th>
<th>Cost &amp; Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>Without significant spikes or reversals of polarity</td>
<td>Maintain instantaneous dc link voltage within device ratings</td>
<td>Sag types A,C,D, &amp; G for characteristic voltage magnitude of 0.15 per unit or lower.</td>
<td>Real current in proportion to available wind power; Reactive current up to system limits.</td>
<td>Minimal additional power devices, ancillary circuits, control, cost and power loss.</td>
<td></td>
</tr>
</tbody>
</table>

**Turbine Protection**

As a result of its large but lightweight mechanical structure and power electronics interface, the DFIG wind turbine is more fragile than a conventional steam cycle driven synchronous generator. The instantaneous currents in the semiconductors in the machine side converter and grid side converter must be held below twice their nominal rating. The electromagnetic torque spikes should be minimized, and be free of any reversals in polarity that would induce gearbox backlash. The voltage in the dc link should not exceed the blocking voltage of the semiconductors in the power converters to prevent their destruction.
Grid Connection

The grid connection requirements vary somewhat depending country of installation and specific negotiations with utility operator. For the purposes of this analysis, the wind turbine is desired to remain connected to the grid in spite of a sag event at the high voltage side of the interface transformer. Fault types A, C, D, & G are considered and characteristic voltage range which corresponds to 0.15 per unit volts at the PCC are studied. Real current is to be produced in proportion to available power, such that if the wind turbine was producing 0.5 rated power prior to the sag, the grid current provided will remain at 0.5 per unit, in spite of changes to the grid voltage. The remaining current capacity should used to provide positive sequence current for reactive power.

Cost & Complexity

As with any commercial endeavor, it is desirable to mitigate the added costs due to any ride through solution. Second, but not less important, is the desire to minimize system complexity to limit design and maintenance costs and reduce likelihood of failure.

2.5 Fault Ride Through Requirements

Concerns about using wind include competing with alternative uses for the land that may be more highly valued than electricity generation. Other concerns are utility interconnections, the noise produced by the turbine blades, their aesthetic impact, and some reports of birds being killed by flying into the rotors. Another major problem for using wind as an electricity production source is that the wind is intermittent, not always blowing when electricity is needed.
The major challenge is how to integrate this intermittent, uncertain, and non-dispatchable wind power into the power grid. In addition to issues mentioned above, the system should meet the new grid code requirements for wind power plants in many countries (Figure 2-7) include a requirement for low-voltage ride-through (LVRT, also called FRT fault-ride-through) in the event of system faults. The generator must stay online during three phase and single line to ground faults and in a range of grid frequencies. The fault clearing times as well as the voltage dip requirements and the requirements for providing voltage support during the fault, vary in the codes implemented so far (Figure 2-7). The grid code can also include a requirement for reactive power control (f.ex. of 0.95 at the point of interconnection), and the need to supply SCADA data as agreed Figure 2-7.

Figure 2-7. Comparison of fault ride through requirements. Source: Elektrizitätszwirtschaft, 2006.
with the TSO. Additional requirements that are being met when requested include voltage control, active power and frequency control (for example ramp rate control). Verified plant models can also be required to be supplied for simulation purposes (Smith et al., 2007).

The grid code requirements are being met by commercial wind plants entering service today, either through the inherent capability of the wind turbine technology being deployed or through the addition of suitable terminal equipment, such as some combination of static and dynamic shunt compensation.

Increased demands will be placed on wind plant performance in the future. Future requirements are likely to include post-fault machine-response characteristics more similar to those of conventional generators (e.g., inertial response and governor response).
Chapter 3 DFIG Wind Turbine Modeling

3.1 Space Vectors Quantities and Reference Frame Transformation

Complex space vectors, also known as dynamic phasors, are used to compactly represent 3 phase ac quantities. Assuming a balanced three phase set of quantities (where $f$ can be voltage, current or flux):

\[
\begin{align*}
    f_a &= F \cos(\omega t + \varphi_f) \\
    f_b &= F \cos(\omega t + \varphi_f - \frac{2\pi}{3}) \\
    f_c &= F \cos(\omega t + \varphi_f + \frac{2\pi}{3})
\end{align*}
\]  

The constant phasor representation of these time domain quantities (using peak rather than RMS amplitude) is

\[
\begin{align*}
    \vec{F}_a &= Fe^{j\varphi_f} \\
    \vec{F}_b &= Fe^{j(\varphi_f - \frac{2\pi}{3})} \\
    \vec{F}_c &= Fe^{j(\varphi_f + \frac{2\pi}{3})}
\end{align*}
\]  

Instantaneously variable three phase quantities can be collected into a complex vector representation,

\[
\vec{f} = \frac{2}{3} (f_a + af_b + a^2 f_c) = f_q - jf_d,
\]  

where
The stationary $d$-$q$ space vector can also be indicated with a superscript “s” and alternately referred to as an $\alpha$–$\beta$ space vector. For a balanced three phase set (substituting (3-1) into (3-3)) yields

$$\tilde{f} = Fe^{j\phi} e^{j\omega t} = \tilde{F} e^{j\omega t}.$$  \hspace{1cm} (3-5)

If $F$, and $\phi$ are constant, then,

$$\tilde{f} = \tilde{F} e^{j\omega t} = (F_q - jF_d)e^{j\omega t}.$$  \hspace{1cm} (3-6)

For convenience this $d$-$q$ quantity is commonly referred to the synchronously rotating reference frame. This rotating reference frame notation allows for compact development of the dynamic model of the ac electrical system as explained in detail in [26]. An illustration of the axes conventions appears in Figure 3-1. The default convention assumed here aligns the $q$-axis with the positive real axis and the $d$-axis with the negative imaginary

![Figure 3-1. Conventions and notation of complex vectors and reference axes](image-url)
Rotation of a stationary complex vector into a reference frame aligned with a space vector, \( \vec{\alpha} \), is

\[
\tilde{f}^\alpha = \tilde{f}^e = f^e - jf^d = Fe^{j(\omega t + \phi_a - \theta)}.
\]  

(3-7)

If \( F \) and \( \phi_f \) are constant, and \( \theta_a = \omega t + \phi_a \)

\[
\tilde{f}^\alpha = Fe^{j(\theta_f - \phi_a)} = \tilde{F}e^{-j(\phi_a)},
\]  

which is a stationary (constant) complex vector, where

\[
\tilde{F}^\alpha = (F^e - jF^d).
\]  

(3-9)

One common quantity for reference frame alignment is the positively rotating synchronous frame vector, designated by superscript “e” where \( \theta_e = \omega t + \theta \). In this case,

\[
\tilde{f}^e = Fe^{j\theta_e} = \tilde{F}.
\]  

(3-10)

If a space vector quantity is unbalanced, it is common to break it into positive, negative and zero sequence components. Absent a zero sequence component, any three phase quantity can be represented with positive and negative sequence components in the stationary reference frame as

\[
\tilde{f}^s = \tilde{F}^s e^{j\omega t} + \tilde{F}^s* e^{-j\omega t},
\]  

(3-11)

or equivalently

\[
\tilde{f}^s = (F^s - jF^s*) e^{j\omega t} + (F^s* + jF^s) e^{-j\omega t},
\]  

(3-12)

Where
A quantity referred to the positively rotating synchronous reference frame is designated with superscript “e” under nominal (balanced) conditions. The superscript “p” is used when considering quantities that might be unbalanced.

### 3.2 DFIG Machine Model

The wound rotor induction generator (WRIG) is usually fed by the stator and by the rotor, which is why it is frequently called a doubly-fed induction generator (DFIG) in the literature [27].

A circuit schematic of the T-model of the DFIG electrical circuit in stationary reference frame is presented in Figure 3-2 [27]. The T-model is so named for the arrangement of the machine’s inductances. The machine magnetic model is assumed to be linear and the iron losses are neglected.

![T-model of the DFIG electrical circuit in stationary reference frame](image)

Figure 3-2. T-model of the DFIG electrical circuit in stationary reference frame
The flux linkage space vector of the stator winding and of the referred rotor winding related to the winding currents by the following equations [27].

\[ \tilde{\psi}_s = (L_{Lm} + L_m)\tilde{i}_s + L_m\tilde{i}_r \quad (3-14) \]
\[ \tilde{\psi}_r = (L_{Lm})\tilde{i}_s + (L_{dr} + L_m)\tilde{i}_r \quad (3-15) \]

For the stator, the induced voltage is the rate of change with time of the flux linkage. The space vector representing the stator and the rotor voltages is given by

\[ \tilde{v}_s = r_s\tilde{i}_s + \frac{d\tilde{\psi}_s}{dt} \quad (3-16) \]
\[ \tilde{v}_r = r_r\tilde{i}_r + \frac{d\tilde{\psi}_r}{dt} - j\omega_m\tilde{\psi}_r \quad (3-17) \]

For an induction machine that can be assumed to be magnetically linear, the equivalent circuit of Figure 3-2 is actually more complex than is necessary. It contains three inductances parameters. By use of simple change of variable, a mathematically equivalent circuit with only two inductances can be produced.

A set of linkage-current relations are stated in equation (3-14) and (3-15). Suppose we introduce a new set of rotor variables related to the original set by

\[ \tilde{\psi}_r = \gamma\tilde{\psi}_r \quad (3-18) \]

and

\[ \tilde{i}_r = \frac{\tilde{i}_r}{\gamma} \quad (3-19) \]
Substitute of these new variables into the flux-linkages relations of equations (3-14) and (3-15) gives

\[ \psi_s = (L_{ih} + L_m)\tilde{i}_s + \gamma L_m \tilde{i}_r \]  

\[ \psi_r = \gamma^2 (L_{ir} + L_m)\tilde{i}_r + \gamma L_m \tilde{i}_s \]  

The chose of the value of \( \gamma \) can be made arbitrarily without changing the validity of equation (3-20) and (3-21). Suppose we chose that value

\[ \gamma = \frac{L_{ih} + L_m}{L_m} = \frac{L_M}{L_m} \]  

Then, equation (3-20) and (3-21) can be written as

\[ \psi_s = L_M \tilde{i}_s + L_M \tilde{i}_r \]  

\[ \psi_r = L_M \tilde{i}_s + (L_{ir} + L_M)\tilde{i}_r \]  

In which the total effective leakage inductance is

\[ L_L = \gamma L_{ih} + \gamma^2 L_{ir} \]  

The transient relations of equations (3-16) and (3-17) now can be written as

\[ \ddot{v}_s = R_S \dot{i}_S + \frac{d\psi_s}{dt} \]  

\[ = R_S \dot{i}_S + L_M \frac{di_S}{dt} + L_M \frac{d\tilde{i}_r}{dt} \]  

\[ \ddot{v}_r = R_R \dot{i}_r + \frac{d\psi_r}{dt} - j\omega_m \psi_r \]  

\[ = R_R \dot{i}_r + \left( \frac{d}{dt} - j\omega_m \right)[L_M \tilde{i}_s + (L_{ir} + L_M)\tilde{i}_r] \]
The effective rotor resistance \( R_r \) in this expression is related to the resistance \( r \) by

\[
R_r = \gamma^2 r, \tag{3-29}
\]

With this change of variable and the revised notation for reflected rotor quantities, the relations of equations (3-27) and (3-29) can be incorporated into the equivalent circuit of Figure 3-3.

![Figure 3-3. Γ-model of the DFIG electrical circuit in stationary reference frame](image)

This equivalent circuit in Figure 3-4 is called the Γ equivalent circuit. The voltage \((- j \omega_m \bar{\psi}_r)\) in Γ equivalent circuit is related to the voltage \((- j \omega_m \bar{\psi}_r)\) in the Τ equivalent circuit by

\[
-j \omega_m \bar{\psi}_r = \gamma(- j \omega_m \bar{\psi}_r) \tag{3-30}
\]

For the wound-rotor machine, the rotor terminal voltage \( \bar{v}_r \) of Figure 3-3 can be transformed to

\[
\bar{v}_r = \bar{v}_r \gamma \tag{3-31}
\]
in the \( \Gamma \) equivalent circuit. Also, any circuit elements connected to the slip rings of a wound-rotor machine can be similarly transformed to be incorporated into the circuit of Figure 3-3.

The power flow through the machine can be found using the equivalent circuit model of Figure 3-3. The instantaneous power entering the stator windings can be found from the space vectors of stator current and stator voltage using the expression

\[
P_s = \frac{3}{2} \Re(\tilde{v}_s^* \tilde{i}_s)
\]  

(3-32)

For wound-rotor machine, the power output would be given by

\[
P_o = -\frac{3}{2} \Re(\tilde{v}_R^* \tilde{i}_R)
\]  

(3-33)

and the mechanical power output is

\[
P_m = -\frac{3}{2} \omega_m \Im(\tilde{v}_R^* \tilde{i}_R)
\]  

(3-34)

the instantaneous torque by a p-pole machine is then given by

\[
T = -\frac{3P}{4} \Im(\tilde{v}_R^* \tilde{i}_R)
\]  

(3-35)

Alternate expression for the torque can be derived by noting that all components of flux linkage in inductance elements are collinear with their corresponding currents and thus do not contribute to the imaginary component in the torque expression. Thus, with a appropriate substituting from (3-14) and (3-15) into (3-35), it can be shown that
This torque is applied to the mechanical system including the mechanical load plus the inertia and loss torque of the motor itself. This torque can be described as

\[ T = \frac{3p}{4} \mathcal{Z}(\bar{\psi}_r^*, \bar{i}_r) \]  

(3-36)

The transient performance of the machine can be described from the three differential equations (3-26), (3-28) and (3-37) in vector state space representations as

\[
\begin{align*}
\frac{d\bar{\psi}_s}{dt} &= \bar{v}_s - R_R \bar{i}_R \\
\frac{d\bar{\psi}_r}{dt} &= j\omega_m \bar{\psi}_r - R_R \bar{i}_R + \bar{\psi}_r \\
\frac{d\omega_{mech}}{dt} &= -\frac{1}{J} \left[ -\frac{3p}{4} \mathcal{Z}(\bar{\psi}_r^*, \bar{i}_r) \right] - T_l
\end{align*}
\]  

(3-38)

3.3 Steady State Operation

It is well known that the breakdown in the flow of mechanically generated power out of the DFIG stator and rotor terminals depends only on the machine slip if the electrical losses in the machine are neglected. This is a reasonable first order approximation, as the electrical drive trains of DFIG wind turbines commonly achieve efficiencies between 95% to 98%[28].
The power flow breakdown is a function of the fundamental physics of the DFIG, and is not in any way dependent on the Rotor side converter/Grid Side Converter architectures or specific control algorithms. The net mechanical shaft power input to the machine \(P_m\) splits between the stator circuit \(P_s\) and rotor electrical circuit \(P_R\) following the relationships:

\[
P_s = \frac{P_m}{1-s} \quad (3-39)
\]

\[
P_R = \frac{-sP_m}{1-s} \quad (3-40)
\]

Since there is no significant energy storage or dissipation in the dc link, the power entering the dc bus from the Rotor Side Converter must leave through the Grid Side Converter. Thus,

\[
P_{\text{Grid Side Converter}} = \frac{-sP_m}{1-s} \quad (3-41)
\]

The power delivered to the Grid Side Converter (GSC) and stator windings sum to yield the total power delivered to the Point of Common Coupling (PCC), which is also equal to the mechanical shaft power in the case of zero losses. The power flow breakdown is illustrated graphically in Figure 3-4.
The mechanical power is related to the cube of the rotor speed, up to the maximum operating speed, typically 1.2 to 1.25 per unit. A plot of the total (mechanical) generated, stator and GSC powers over a typical speed range is presented in Figure 3-5.

Figure 3-5. Total generated, stator and Grid Side Converter (GSC) power vs. rotor speed (bottom scale) and slip (top scale)[28].
When operating sub-synchronously (positive slip), the GSC draws power from the grid and feeds it to the rotor circuit via the Rotor Side Converter (RSC) as indicated in Figure 3-6.

![Figure 3-6. Subsynchronous generating mode (s>0).](image)

When the rotor speed is super-synchronous (negative slip) power flows from the rotor circuit RSC and is fed to the grid via the GSC, as indicated in Figure 3-7.

![Figure 3-7. Supersynchronous generating mode (s<0).](image)

The torque-slip curve for DFIG in sub and supersynchronous modes can be seen in Figure 3-8.
3.4 DFIG Reactive Power Analysis

If the RSC injects the reactive power ($jQ$) in accordance with equation (3-42) the stator reactive power can be programmed as indicated by equation (3-43).

$$Q_{\text{Rotor}} = s \omega_e \frac{3}{2} (j \psi_{qdr} i_{qdr})$$  \hspace{1cm} (3-42)

$$Q_{\text{Stator}} = \frac{3}{2} L_s (i_{qdr})^2 - \left( \frac{Q_{\text{Rotor}}}{s} \right)$$  \hspace{1cm} (3-43)

If the reactive power injected in the rotor it will be subtracted from the reactive power injected in the stator. Theoretically, leading power factor ($Q<0$) is possible at the cost of lagging power factor in the rotor. The rotor losses become for high slip.
In addition, higher slip required a higher rotor voltage, and leading power factor at the utility side become a very difficult scheme to implement. However, decreasing VAR from the utility side is possible to implement.
Chapter 4 Effect of Grid Fault on DFIG

4.1 Analysis under normal operation

In this section, the DFIG T-model in stationary reference frame is used to analyze the effect of grid fault on the generator. In this model, the rotor variables are referred to the stator side for simplicity. A similar analysis for balanced sags has also been presented in [29]. Using motor convention, the stator and rotor voltages in $abc$ frame can be expressed as:

$$\bar{v}_s = r_i \bar{i}_s + \frac{d \bar{\psi}_s}{dt} \quad (4-1)$$
$$\bar{v}_r = r_r \bar{i}_r + \frac{d \bar{\psi}_r}{dt} - j \omega_m \bar{\psi}_r \quad (4-2)$$

The stator and rotor fluxes are given by:

$$\bar{\psi}_s = (L_{ls} + L_m) \bar{i}_s + L_m \bar{i}_r \quad (4-3)$$
$$\bar{\psi}_r = (L_m) \bar{i}_s + (L_{lr} + L_m) \bar{i}_r \quad (4-4)$$

Figure 4-1 shows the equivalent circuit corresponding to the above equations.

Figure 4-1. T-model of the DFIG electrical circuit in stationary reference frame
For the purpose of the rotor over-current analysis during the short circuit, the rotor voltage from the converter point of view is one of the most important variables in the analysis. This voltage is induced by the variation of the stator flux, which can be calculated by deriving $i_s$ from (4-3) and substituting into (4-4)

$$\tilde{\psi}_r = \frac{L_m}{L_s} \tilde{\psi}_s - \sigma L_s \tilde{i}_r, \quad \sigma = 1 - \frac{L_m^2}{L_s L_r}$$  \hspace{1cm} (4-5)

Thus, the rotor voltage can be found by combining (4-2) and (4-5)

$$\tilde{v}_r = \frac{L_m}{L_s} \left( \frac{d}{dt} - j \omega_m \right) \tilde{\psi}_s + \left( R_r + \sigma \omega_m \left( \frac{d}{dt} - j \omega_m \right) \right) \tilde{i}_r$$  \hspace{1cm} (4-6)

The rotor voltage given by (4-6) can be divided into two terms. The first one is called open circuit voltage ($\tilde{v}_{r0}$) and as it can be seen from (4-6), this term depends on the stator flux. The second term is smaller and it is caused by the voltage drop on both the rotor resistance $R_r$ and the rotor transient inductance $\sigma L_r$. From (4-6), when there is no current in the rotor circuit, the rotor voltage due to the stator flux is ($\tilde{v}_{r0}$).

$$\tilde{v}_{r0} = \frac{L_m}{L_s} \left( \frac{d}{dt} - j \omega_m \right) \tilde{\psi}_s$$  \hspace{1cm} (4-7)

**4.1.1 Rotor Voltage under Normal Operation**

In normal operation, the stator voltage space phasor is rotating vector of constant amplitude $V_s$ that rotates at synchronous speed $\omega_s$. 
\[ \tilde{v}_s = V_s e^{j\omega t} \quad (4-8) \]

If the stator resistance \( R_s \) is neglected, the expression for the stator flux can be obtained from (4-1) and (4-8)

\[ \tilde{\psi}_s = \frac{V_s}{j\omega_s} e^{j\omega t} = \Psi_0 e^{j\omega t} \quad (4-9) \]

Where \( \Psi_0 \) being the stator flux phasor.

By substituting (4-9) in (4-7), the term for the rotor voltage caused by the stator flux becomes

\[ \tilde{v}_{r0} = j\omega_r \frac{L_m}{L_s} \tilde{\psi}_s = \frac{\omega_r L_m}{\omega_s L_s} V_s e^{j\omega t} \quad (4-10) \]

The rotor voltage caused by the stator flux is proportional to the slip frequency that is the difference between the synchronous and the rotor speed. The amplitude of the voltage \( \tilde{v}_{r0} \) can be written as a function of the amplitude of the stator voltage

\[ V_{r0} = V_s \frac{L_m}{L_s} s \quad (4-11) \]

where \( s \) is the slip \( (s = \frac{\omega_r}{\omega_s}, \omega_r = \omega_s - \omega_m) \).

The previous equations describe the rotor voltage when there is no rotor current. However, during normal operation, the rotor converter controls the rotor current in order to achieve the active and reactive powers. The voltage in the rotor terminals that has to be generated by the converter is

\[ \tilde{v}_r = \tilde{v}_s \frac{L_m}{L_s} s + \left( R_r + \sigma L_r \left( \frac{d}{dt} - j\omega_m \right) \right) \tilde{i}_r \quad (4-12) \]
The rotor resistance and the transient reactance are typically small. In addition, the rotor current frequency is also small \( f_r < 10 \text{ Hz} \). As a result, the voltage at the rotor terminals does not considerably differ from \( \bar{v}_{r0} \).

### 4.2 Analysis under 100% Symmetrical Voltage Sag

At the moment of the short circuit \( t_0 = 0 \), the open circuit rotor voltage due to the stator flux is given by:

\[
\bar{v}_{r0} = -\frac{L_m}{L_s} \left( \frac{1}{\tau_s} + j\omega_m \right) \Psi_0 e^{j/\tau_s}, \quad \Psi_0 = \frac{V_s}{j\omega_s} e^{j\phi_{\Psi_0}} \tag{4-13}
\]

where \( \Psi_0 \) is the stator flux just before the short circuit.

The voltage is a space vector fixed to the stator. Its amplitude decreases exponentially to zero. With respect to the rotor, this voltage rotates reversely with rotor angular frequency of \( \omega_{\Psi_0} \).

\[
\bar{v}''_{r0} = -\frac{L_m}{L_s} \left( \frac{1}{\tau_s} + j\omega_m \right) \Psi_0 e^{j/\tau_s} e^{-j\omega_{\Psi_0}t} \tag{4-14}
\]

Figure 4-2 shows the rotor voltage behavior during three phase short circuit with a slip of -20%. As it can be seen the magnitude of the rotor voltage \( v_{r0} \) reaches its maximum value at the moment of the short circuit. Using (4-14) and neglecting the term \( 1/\tau_s \) due to its small value

\[
V_{r0} \approx \frac{L_m}{L_s} \frac{\omega_m}{\omega_s} V_s = \frac{L_m}{L_s} (1-s) V_s \tag{4-15}
\]
According to (4-15), $V_r$ is proportional to $1-s$. Since the slip is in the range of -0.2 to 0.2, it can be concluded that the amplitude of the voltage induced on the rotor winding during short circuit is close to stator voltage. It can even be higher if the machine operates at super-synchronous speed.

![Graph](image)

Figure 4-2. Rotor voltage with 0.2 slip and 100ms stator time constant.

Figure 4-3 shows the transient of the stator flux trajectory due to the stator voltage before and after the short without compensation. At the short circuit moment the stator flux freezes and its magnitude decrease to zero according to the stator time constant causing higher induced voltage in the rotor circuit.
4.3 Analysis under Partial Symmetrical Voltage Sag

For this analysis, we assume that the generator is running at the nominal stator voltage, when at $t = 0$ the stator voltage dips from $\bar{v}_{s-n}$ to $\bar{v}_s$, where $\bar{v}_{s-n}$ is the nominal stator voltage.

\[
\bar{v}_s = \begin{cases} 
\bar{v}_{s-n} & \text{for } t < 0 \\
\bar{v}_s & \text{for } t \geq 0 
\end{cases}
\]  

(4-16)

\[
\bar{v}_s = r_s \bar{i}_s + \frac{d\bar{\psi}_s}{dt}
\]  

(4-17)

Solving for $\bar{i}_s$ from (4-3) and substituting in (4-17) yields:

\[
\frac{d\bar{\psi}_s}{dt} = \bar{v}_s - \frac{r_s}{L_s} \bar{\psi}_s
\]  

(4-18)
Neglecting the stator resistant, the stator flux can be written as:

$$\vec{\psi}_{s-n}(t < 0) = \frac{\vec{v}_{s-n}}{j\omega_s}$$

(4-19)

Replacing phasor of $\vec{v}_{s-n}$ with $V_{s-n}e^{j\omega t}$, we achieve:

$$\vec{\psi}_{s-n}(t < 0) = \frac{V_{s-n}}{j\omega_s} e^{j\omega t}$$

(4-20)

A balanced voltage sag at the stator terminal, it is assumed to be a step change of the stator voltage. We define $h$ as the ratio of the stator voltage before and after the sag as follows.

$$h = \frac{\left| \vec{v}_s \right|}{\left| \vec{v}_{s-n} \right|}$$

(4-21)

Neglecting the stator resistant, stator flux response to a voltage sag occurring at $t = 0$ is explained as follows.

$$\vec{\psi}_s(t) = \frac{V_s}{j\omega_s} e^{j\omega t} + \left( \frac{V_{s-n} - V_s}{j\omega_s} \right) e^{-\frac{t}{\tau_s}}$$

(4-22)

Combining (4-21) and (4-22), the stator flux can be described as:

$$\vec{\psi}_s(t) = \vec{\psi}_{s-n}(h + (1 - h)e^{-\frac{(j\omega_s + \frac{1}{\tau_s})t}})$$

(4-23)

The second component of (4-23), which describe stator flux, “freezes” according to faraday’s law, (apart from the slow exponential decay). This “frozen” part appears to produce a transient oscillatory stator flux that decays with the stator time constant.
By substituting (4-23) in (4-7), the rotor voltage caused by the stator flux, in stationary reference frame, is achieved as follows.

\[
\tilde{v}_{ro} = |\tilde{v}_{s-n}| \frac{L_m}{L_s} (h.s.e^{j\omega t} - (1 - h)(1 - s)e^{-j\omega t})
\]  

(4-24)

The two terms in the (4-24) are different in nature. The first part is generated by the new grid voltage and its amplitude is small because it is proportional to the slip. The second voltage is the transient term and its amplitude is proportional to the depth of the voltage dip and to 1-s. This is the voltage that causes huge rise in the rotor current. Equation (4-24) is the rotor voltage when there is no rotor current. However, during the normal operation, the rotor converter controls the rotor current in order to achieve the active and reactive reference power. The voltage in the rotor terminals that has to be generated by the converter is provided by (4-25).

\[
\tilde{v}_r = |\tilde{v}_{s-n}| \frac{L_m}{L_s} (h.s.e^{j\omega t} - (1 - h)(1 - s)e^{-j\omega t}) + \left( R_r + \sigma L_r \left( \frac{d}{dt} - j\omega_m \right) \right) \tilde{i}_r
\]  

(23)

For a short circuit at turbine terminal, the above analysis is applied by setting \( h \) to 0. Figure 4-4 shows the stator flux trajectory for voltage sag type(A) with \( h=0.5 \).
4.4 Voltage Sag Simulation

The following sags are applied to the terminal of the wind turbine with initial rotor speed of 1.2 pu: Type A, C, D & G sags of different value of $h$. Plots of the wind turbine stator voltage, stator current, and rotor current response are presented in Figure 4-5 to Figure 4-9. Due to magnetic coupling between the stator and rotor circuits, stator flux changes produce a rotor EMF as described in the previous section. The deeper voltage sag and deviations in the stator flux cause the RSC to go into over-modulation, resulting in loss of rotor current regulation and very high per unit rotor currents. The uncontrolled rotor currents exceed the RSC semiconductor device ratings and destroy the RSC. In addition, this also precipitates very large shaft torque transient spikes.
Figure 4-5. Simulation response of a 2 MW DFIG wind turbine to type “A” voltage sag with $h=0.15$. 
Figure 4-6. Simulation response of a 2 MW DFIG wind turbine to type “C” voltage sag with $h=0.05$. 
Figure 4-7. Simulation response of a 2 MW DFIG wind turbine to type “D” voltage sag with $h=0.05$. 
Figure 4-8. Simulation response of a 2 MW DFIG wind turbine to type “G” voltage sag with $h=0.05$. 
Figure 4-9. Simulation response of a 2 MW DFIG wind turbine to type “G” voltage sag with $h=0.95$. 
Chapter 5 Series Voltage Compensation for DFIG
Wind Turbine Low Voltage Ride-Through Solution

5.1 Current Solutions

This section compares the conventional state of the art accommodations for voltage disturbance ride through for the classical DFIG. Most of the proposed solutions involve circuit modifications, with one exception which proposes a modified RSC current control strategy to during sag events. Each of these accommodations is capable of riding through a voltage sag with varying degrees of acceptability. The properties of each approach are described in the following subsections.

5.1.1 Rotor Crowbar (3 phase SCRs)

Modifications to the conventional DFIG architecture have been proposed to enhance PCC voltage sag ride through capability. In [30] the authors present a three phase SCR and resistor crowbar circuit in parallel with the SCR, which is capable of riding through a balanced voltage sag down to 15% of nominal voltage. A schematic of this electrical architecture is shown in Figure 5-1.
The challenge with this approach is that the rotor crowbar resistor sizing is driven by conflicting requirements:

1- Too large a resistance and the MSC is over-voltaged and destroyed
2- Too small and large rotor current produces excessive torque spikes.
3- A parametric study performed in [31] shows that the optimal rotor crowbar resistance is approximately 200 times the nominal rotor resistance. Authors of [63] found that for this optimal resistance torque spikes on the order of 5 pu are still prevalent for balanced sags.
4- When the crowbar engages the DFIG effectively converters to a conventional induction generator with a large rotor resistance.

As a result the DFIG (except for the GSC) becomes a consumer of reactive power from the grid, which is precisely contrary to the required and preferred operation with regards to grid stability.
5.1.2 Rotor Active PWM Crowbar

An alternate version of the rotor crowbar employs a three phase diode bridge rectifier and single SCR controlled resistor, as shown in Figure 5-2, which performed similarly for a balanced sag down to 20% of nominal in [32] and 35% of nominal in [33].

![Schematic of conventional DFIG wind turbine architecture with rotor active PWM crowbar](image)

Figure 5-2. Schematic of conventional DFIG wind turbine architecture with rotor active PWM crowbar.

5.1.3 Rotor Crowbar (3 phase SCRs) and DC Link Chopper crowbar

In general the RSC remains connected to the rotor circuit during the sag event, even during engagement of the rotor crowbar. Even if the IGBTs are ungated (controlled to be off) it will still operate as a rectifier. Depending on the resistance of the rotor crowbar resistor this can cause the dc link voltage to rise uncontrollably. Thus it is common to add a resistive chopper circuit to the dc link to dissipate excess energy, as shown in Figure 5-3.
5.1.4 **Rotor Crowbar and Stator Switch**

In [34,35] the authors propose a DFIG system with 3 pairs of anti-parallel GTOs or force commutated SCRs in series with the stator winding connection to the grid, in addition to crowbar in parallel with the RSC, as illustrated Figure 5-4.
This approach has been shown to produce peak stator current and shaft torque of approximately 2 per unit during sag events. However, the rotor crowbar must also be included for emergency backup protection of the RSC. In addition, the RSC must be oversized slightly to handle the rapid de-fluxing of the DFIG during the sag event.

### 5.2 Proposed Solution for DFIG Wind Turbine Low Voltage Ride-Through

#### 5.2.1 Analytical Analysis for the Proposed Solution

To start analyzing the proposed solution, it is assumed that the generator is operating at normal conditions when at time $t_0$ a three-phase short circuit occurs:

$$
\dot{\bar{v}}_s = \begin{cases} 
V_s e^{j\omega_s t} & \text{for } t < t_0 \\
0 & \text{for } t \geq t_0 
\end{cases}
$$  \hspace{1cm} (5-1)

As soon as the short circuit is detected, we apply a voltage vector of $\bar{v}_c$, where $|\bar{v}_c| = |\bar{v}_s|$ and $\tau_i$ is the time constant to be quantified later from energy equations of the system.

$$
\dot{\bar{v}}_c = \begin{cases} 
0 & \text{for } t < t_0 \\
V_c e^{j\omega_s t} e^{-\tau_i} & \text{for } t \geq t_0 
\end{cases}
$$  \hspace{1cm} (5-2)

Under this condition, the expression for the stator flux can be obtained from (3-16) and (3-17) as follows:

$$
\frac{d\bar{\psi}_s}{dt} = \bar{v}_s - \frac{R_s}{L_s} \bar{\psi}_s
$$  \hspace{1cm} (5-3)

Substituting $\bar{v}_s = \bar{v}_c e^{-\tau_i}$, the solution to this non-homogeneous first order differential equation can be found. Assuming zero delay for the compensation, the homogeneous part
of (5-3) can be eliminated. This part corresponds to the transient flux. Solving (5-3) for stator flux, we get:

\[
\psi_s = \frac{V_c}{\left(j\omega_s - \frac{1}{\tau_1} + \frac{1}{\tau_s}\right)} e^{j\omega_s t} e^{-\gamma t / \tau_s} \quad (5-4)
\]

Substituting (5-4) in (4-7), the rotor voltage induced from stator flux is obtained as follows:

\[
\tilde{v}_r = \frac{L_m}{L_s} \left(\frac{d}{dt} - j\omega_m\right) \frac{V_c}{\left(j\omega_s - \frac{1}{\tau_1} + \frac{1}{\tau_s}\right)} e^{j\omega_s t} e^{-\gamma t / \tau_s} \quad (5-5)
\]

\[
\tilde{v}_r = \left(\frac{L_m}{L_s} V_c \right) \left(j\omega_s - j\omega_m\right) \frac{1}{\tau_1} e^{j\omega_s t} e^{-\gamma t / \tau_s} \quad (5-6)
\]

This voltage is a state vector that rotates at synchronous frequency. Its amplitude decreases exponentially with the time constant of \(\tau_1\). With respect to the rotor, this voltage rotates reversely at slip frequency. Since the time constant for large machines is much greater than 200ms, then we can assume \(\tau_1 \ll \tau_s\) and the rotor open circuit voltage can be written in terms of slip as follows:

\[
\tilde{v}_{r0} = \left(\frac{L_m}{L_s} V_c \right) e^{-\gamma t / \tau_1} e^{i(\omega_s - \omega_m) t} \quad (5-7)
\]

Substituting (5-7) into (4-12) the rotor voltage connected to the converter can be found:

\[
\tilde{v}_r = \tilde{v}_{r0} e^{-\gamma t / \tau_1} + \left(R_s + \sigma L_s \left(\frac{d}{dt} - j\omega_m\right)\right) \tilde{i}_r \quad (5-8)
\]
As described above, the magnitude of the rotor voltage at the moment of the short circuit \((t \geq t_0)\) due to the stator flux equals to the magnitude of the stator voltage at normal operation, which exponentially decreases to zero by stator time constant, as shown in Figure 5-5. According to (5-8), the time constant of rotor voltage due to the stator flux no longer depend on the stator time constant. It totally depends on the time constant of \(\tau_1\). This feature allows for dealing with output energy of wind turbine during the short circuit as well as keeping the rotor side inverter current within acceptable limit.

Figure 5-6 shows the transient of the stator flux trajectory due to the stator voltage before and after the short without compensation. At the short circuit moment the stator flux freezes and its magnitude decrease to zero according to the stator time constant causing higher induced voltage in the rotor circuit.
Figure 5-6. Stator flux trajectory transient without any compensation.

Figure 5-7 shows the transient of the stator flux trajectory due to the stator voltage before and after the short with compensation. At the short circuit moment, the compensator injects a voltage to the stator circuit to keep the stator flux rotating at synchronous speed but its magnitude decreases exponentially with the time constant of $\tau_1$. Since the stator flux keeps rotating during the short circuit transient, the induced voltage in the rotor due to the stator flux is kept at its nominal valve.
5.2.2 Control Technique

In this section, a three-phase bidirectional series voltage compensator is described. Its configuration is shown in Figure 5-8. The series converter consists of six power electronics switches and is rated at about 20% of the output of the wind turbine. It is connected via transformer in series with the ac line. The passive filter formed by $L_i$ and $C_i$ removes switching frequency the harmonics from output of the series converter. Also, $L_i$ acts as a link between filter and the system.
Figure 5-8. Schematic of DFIG wind turbine with series grid side converter (SGSC) connected via series injection transformer for the proposed LVRT solution.

The state space equations of one phase of this system in continuous time-domain, as described in [36], are as follows:

\[
\begin{align*}
C_1 \frac{dV_{fa}}{dt} &= i_{t_{1a}} - ni_{sa} \quad (5-9) \\
L_1 \frac{di_{t_{1a}}}{dt} &= V_{\phi_{1a}} - V_{fa} \quad (5-10)
\end{align*}
\]

Where \( n \) is the turn ratio of the series transformer: \( n = \frac{V_{fa}}{V_{fa}} \). Considering \( V_{\phi} \) and \( i_{t_{1}} \) as state variables, the state space model for series converter is given by:

\[
\begin{bmatrix}
V_{t_{1o}} \\
i_{t_{1,2o}}
\end{bmatrix} = A \begin{bmatrix}
V_{t_{1o}} \\
i_{t_{1,2o}}
\end{bmatrix} + B V_{t_{2o}} + C n i_{uo} \quad (5-11)
\]

Where
where

$$\Phi = e^{ATs} = \begin{bmatrix} \cos \omega_0 T_s & \frac{\sin \omega_0 T_s}{\omega_0 C_1} \\ -\frac{\sin \omega_0 T_s}{\omega_0 L_1} & \cos \omega_0 T_s \end{bmatrix}$$

$$\Psi = (e^{ATs} - I_1) A^{-1} B = \begin{bmatrix} 1 - \cos \omega_0 T_s \\ \frac{1}{\omega_0 L_1} \sin \omega_0 T_s \end{bmatrix}$$

and

$$\Gamma = (e^{ATs} - I_1) A^{-1} C = \begin{bmatrix} -\frac{1}{\omega_0 C_1} \sin \omega_0 T_s \\ 1 - \cos \omega_0 T_s \end{bmatrix}$$

Where $\omega_0$ is the angular resonance frequency of $L_1$ and $C_1$. The sampling frequency of the system is always considered much higher than the resonance frequency of $L_1$ and $C_1$. With this assumption, equation (5-12) is simplified to (5-13). This conversion is valid for almost $f_s \geq 20 f_0$. 

$$A = \begin{bmatrix} 0 & 1/C_2 \\ -1/L_2 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1/L_2 \end{bmatrix} \quad \text{and} \quad C = \begin{bmatrix} -1/C_2 \\ 0 \end{bmatrix}.$$
\[
\begin{bmatrix}
V_{Fa}(k+1) \\
i_{L1a}(k+1)
\end{bmatrix} = 
\begin{bmatrix}
1 & \frac{T_s}{C_1} \\
-\frac{T_s}{L_1} & 1
\end{bmatrix}
\begin{bmatrix}
V_{Fa}(k) \\
i_{L1a}(k)
\end{bmatrix} + 
\begin{bmatrix}
0 & \frac{T_s}{L_1} \\
-T_s/C_1 & 0
\end{bmatrix}
\begin{bmatrix}
V_{P1a}(k) \\
m_{1a}(k)
\end{bmatrix} \tag{5-13}
\]

- **Voltage and Current Deadbeat Controller for Series converter**

The current equation of series converter according to (5-13) is given by

\[
i_{L1a}(k+1) = i_{L1a}(k) + \frac{T_s}{L_1} [V_{P1a}(k) - V_{Fa}(k)] \tag{5-14}
\]

Alternatively, this equation can be achieved by converting (5-9) from differential equation to difference equation. The same suggestion of \( f_s > 20 f_{oi} \) has to be made for this conversion as well. If \( V_{Fi} \) and \( i^*_{L1a} \) are considered constant over the next switching period, the output voltage of the series converter, which corrects the error after two-sampling periods, is described by [6].

\[
V_{P1a}(k+1) = V_{Fi}(k+1) + \frac{L_1}{T_s} [i^*_{L1a}(k+1) - i_{L1a}(k+1)] \tag{5-15}
\]

A linear estimation of \( V_{Fi}(k+1) \) can be achieved from previous values

\[
V_{Fi}(k+1) = V_{Fi}(k) + [V_{Fi}(k) - V_{Fi}(k-1)]
\]

\[
= 2V_{Fi}(k) - V_{Fi}(k-1) \tag{5-16}
\]

By substituting (5-14) and (5-16) in (5-15) and updating reference current for in every two-sampling periods, the deadbeat digital control for series converter is described by
\[ V_{p_{1a}}(k+1) = \frac{L}{T_s} [i_{L1a}^*(k) - i_{L1a}(k)] - V_{p_{1a}}(k) + 3V_{F_{a}}(k) - V_{F_{a}}(k-1) \] 

Equation (5-17) ensures that the current error between \( i_{L1a} \) and \( i_{L1a}^* \) at time \( k + 2 \) goes to zero with a delay of two-sampling periods. Avoiding interaction between voltage and current control loops, output voltage of series converter \( V_{F_{a}} \) is sampled at half of the current sampling frequency. The voltage equation according to (5-13) is as follows:

\[ V_{F_{a}}(k+1) = V_{F_{a}}(k) + \frac{T_s}{C_1} i_{C1a}(k) \]  

\[ V_{F_{a}}(k+2) = V_{F_{a}}(k+1) + \frac{T_s}{C_1} i_{C1a}(k+1) \]

\[ = V_{F_{a}}(k) + \frac{T_s}{C_1} i_{C1a}(k) + \frac{T_s}{C_1} i_{C1a}(k+1) \]  

As current control is suggested to be deadbeat with a delay of two-sampling periods, capacitor current at time \( k \) and \( k + 1 \) is given by

\[ i_{C1a}(k) = i_{C1a}^*(k-2), \quad i_{C1a}(k+1) = i_{C1a}^*(k-1) \]  

Substituting (5-20) in (5-19) and updating the reference current at each two-sampling periods, \( V_{F_{a}}(k+1) \) is given by

\[ V_{F_{a}}(k+2) = V_{F_{a}}(k) + \frac{2T_s}{C_1} i_{C1a}^*(k-2) \]  

The current of \( i_{C1a}^* \) at time \( k \) which corrects the voltage error of \( V_{F_{a}} \) at time \( k + 4 \) is as follows:
\[ i_{C_1}(k) = \frac{C_1}{2T_s} \left[ V_{F_1}(k) - V_{F_2}(k) \right] - i_{C_1}(k-2) \]  

(5-22)

Block diagram of implementation of voltage and current control of series converter in bypass mode is shown in Figure 5-9.

Figure 5-9. Implementation of the current and voltage control of the series converter.

### 5.5 Energy Calculation for DC Capacitor

During short circuit on the stator, the wind turbine cannot export any power. However, when the compensation is applied, the series converter absorbs all the turbine energy and charges the capacitor. If a decaying time constant applied to the compensation voltage, the absorbed power and capacitor size can be greatly reduced. These two cases are analyzed below.

**Case I:**

In this case, no time constant \((\tau_v)\) is introduced for the voltage compensation and the series converter provides 100% compensation during short circuit. We will have:

\[ E = \int_{t_0}^{t_1} Pdt \]  

(5-23)

Where \(P\) is the incoming power from wind turbine and \(E\) is the energy delivered from \(t_0\) to \(t_1\). At the moment of the short circuit \((t \geq t_0 = 0)\), we have:
\[ P = \sqrt{3} \cdot V \cdot I \]  \hspace{1cm} (5-24)

All this power will be delivered to the capacitor of the compensator. Substituting \( V \) with \( V_c \) in (5-24), we will have:

\[ P = \sqrt{3} \cdot V_c \cdot I \]  \hspace{1cm} (5-25)

Integrating (5-25) over maximum short circuit time (200ms), the total energy delivered is found:

\[ E = \int_{0}^{0.2} \sqrt{3} \cdot V_c \cdot I \]  \hspace{1cm} (5-26)

The capacitor size for this case the can be calculated as:

\[ C = \frac{2E}{\Delta V^2} \]  \hspace{1cm} (5-27)

Where, \( \Delta V \) is the maximum allowable voltage variation of the capacitor. Substituting (5-26) into (5-27), the capacitor size for this case can be obtained.

\[ C = \frac{2 \int_{0}^{0.2} \sqrt{3} V_c \cdot I}{\Delta V^2} \]  \hspace{1cm} (5-28)

In fact, the wind turbine delivers the same power before, during and after the short circuit since the generator does not see the short circuit in this case. Therefore, a large capacitor bank is required to absorb the energy. Figure 5-10 shows the delivered generator power during short circuit with 100% voltage compensation at \( t = 3 \text{s} \).
Figure 5-10. Active power delivered with 100% voltage compensation ($V = V_c$).

Case 2:

In this case, time constant $\tau_1$ is introduced for the voltage compensation.

Substituting $V = V_c e^{-\tau_1}$ in (5-26), we get:

$$E = \int_{0}^{0.2} \sqrt{3} V_c e^{-\tau_1} I$$  \hspace{1cm} (5-29)

And the capacitor size in this case is achieved from the following equation:

$$C = \frac{2E}{\Delta V^2} = \frac{2 \int_{0}^{0.2} \sqrt{3} V_c e^{-\tau_1} I}{\Delta V^2}$$  \hspace{1cm} (5-30)

From above, it can be found that the energy is a function of the time constant $\tau_1$ and can be controlled by changing it. In addition, the capacitor size can also be significantly reduced.
From case 1 and case 2, it can be concluded that the energy that is being extracted from the wind turbine during the short circuit is reduced. The power delivered by the turbine is shown in Figure 5-11. It is exponentially decreased to zero with a time constant of $\tau_1$. In the analysis above, the magnitude of the compensation voltage $V_c$ at $t = t_0$ is assumed to be equal to the magnitude of the system voltage $V$. Because the rotor side converter current rated to twice its nominal current, the magnitude of the compensation voltage $V_c$ at $t \geq t_0$ can be reduced to $V/2$. This technique allows us to reduce the capacitor size.

This case will be demonstrated in the test results section.

**Comparison example for case 1 and case 2:**

For a 1.5MW, 690V Wind turbine it is assumed a 100% voltage compensation for a period of 200ms, during the short circuit, the required capacitance for such a system can be calculated as follows:

1- $\tau_1 = \infty$
Substituting in (5-26), the energy over 200ms can be calculated as

\[ E_1 = \int_{0}^{0.2} 1.5 \cdot 1.5 \cdot t \cdot dt = 300 \text{kJ} \]

If we allow \( \Delta V = 400 \text{V} \) increase in the DC bus voltage for 200ms, then total capacitance

\[ C = \frac{2E}{\Delta V^2} = \frac{2 \times 300 \text{kJ}}{400^2} = 3.75 \text{F} \]

\( \tau_1 = 0.05 \text{s} \)

Substituting in (5-29), the energy over 200ms can be calculated as

\[ E_2 = \int_{0}^{0.2} 1.5e^{-t/0.05} \cdot t \cdot dt = 73.62 \text{kJ} \]

If we allow \( \Delta V = 400 \text{V} \) increase in the DC bus voltage for 200ms, then total capacitance

\[ C = \frac{2E}{\Delta V^2} = \frac{2 \times 73.62 \text{kJ}}{400^2} = 0.92 \text{F} \]

From case 1 and case 2 we can see that the capacitor size is reduced proximally by 75%.

Also, if the stator voltage is compensated by a 50% during the short circuit the KVA rating of the system can be reduced furthermore.

For 50% stator voltage compensation, the total capacitance can be reduced more and it is equal to 0.45F.
Chapter 6 System simulation and Hardware Demonstration

6.1 System Simulation Studies

Simulation studies were performed in support of the analytical studies. A dynamic state based model of the DFIG, electrical circuit, lumped mechanical system and quasi-static aerodynamic system was developed in MATLAB-Simulink. The mechanical system is represented by a lumped inertia, and the power converters are represented by their ideal average circuit equivalent. The controllers are built in the continuous domain, and switch modulation functions include third harmonic injection and effects of inverter modulation limits. A small impedance, representative of the collection transformer leakage, connects the DFIG to grid PCC. Simulation parameters are tabulated in the Appendix.

The key to successful voltage sag ride-through is the reduction in the DFIG stator flux magnitude in concert with the farm collector voltage. This inherently scales the torque production in the machine without modifying the RSC current command, and limits power flow into the dc link from the rotor circuit. The dc link voltage remains within safe bounds without a chopper circuit.

In this section, the effect of 100% and 50% stator voltage compensation, for faults type A, C, D and G, is investigated for different value of the decaying time constant $\tau_i$,
and $h$, to mitigate the stator and rotor current within twice it rated value during the short circuit. The results of proposed LVRT are presented in Figure 5-12 to Figure 5-27. The results reveal the minimum compensation requirements to achieve successful LVRT for different type of voltage sag. It also approve our proposed solution for energy storage system requirements that proposed in section 5-3 to reduce the energy storage system necessary for this type of LVRT.

From the 100% stator voltage compensation cases, we can see that the rotor current kept at 1 pu. Also, The Dc bus, Rotor speed, Active power and reactive power are kept at their initial values that they set to before the voltage sag except for $\tau_1$ smaller than 0.05s. at this point, when we set $\tau_1$ smaller than 0.05s , the stator flux has some dynamics cause the rotor current to have some increase at the moment of the short circuit. This increase can be tolerated as long as its within the RSC rating, which is 2 pu of the rotor nominal current.

From 50% stator voltage compensation, we can see that the rotor current is in fact kept with in the RSC ratings, which is 2 pu of the rotor nominal current. It can bee seen the tradeoff between full or partial stator voltage compensation and how small we can see the decaying time constant $\tau_1$. More study need to be conducted to determined the relationship between decaying time constant $\tau_1$ and the maximum rotor current for both cases (100% and 50% voltage compensation). From initial observation, and a good way to approach this analysis is to look a how deep the voltage dips every after completing one cycle. The deeper the voltage dip the higher rotor current expected.
Figure 5-12. Simulation response of a 2 MW DFIG wind turbine to type “A” voltage sag with $h=0.15$, 100% stator voltage compensation and $r_i = \infty$. 
Figure 5-13. Simulation response of a 2 MW DFIG wind turbine to type “A” voltage sag with \( h=0.15 \), 100% stator voltage compensation and \( \tau = 0.1 \text{s} \).
Figure 5-14. Simulation response of a 2 MW DFIG wind turbine to type “A” voltage sag with $h=0.15$, 100% stator voltage compensation and $\tau_1 = 0.05s$. 
Figure 5-15. Simulation response of a 2 MW DFIG wind turbine to type “A” voltage sag with $h=0.15$, 100% stator voltage compensation and $\tau_1 = 0.01\text{s}$.
Figure 5-16. Simulation response of a 2 MW DFIG wind turbine to type “A” voltage sag with $h=0.15$, 50% stator voltage compensation and $\tau_i = \infty$. 
Figure 5-17. Simulation response of a 2 MW DFIG wind turbine to type “A” voltage sag with \( h=0.15 \), 50% stator voltage compensation and \( \tau_1 = 0.1 \text{s} \).
Figure 5-18. Simulation response of a 2 MW DFIG wind turbine to type “A” voltage sag with $h=0.15$, 50\% stator voltage compensation and $\tau_i = 0.05$s.
Figure 5-19. Simulation response of a 2 MW DFIG wind turbine to type “A” voltage sag with $h=0.15$, 50% stator voltage compensation and $\tau_1 = 0.01$s.
Figure 5-20. Simulation response of a 2 MW DFIG wind turbine to type “C” voltage sag with $h=0.05$, 100% stator voltage compensation and $\tau_1 = \infty$. 
Figure 5-21. Simulation response of a 2 MW DFIG wind turbine to type “C” voltage sag with $h=0.05$, 100% stator voltage compensation and $\tau_1 = 0.1\text{s}$.
Figure 5-22. Simulation response of a 2 MW DFIG wind turbine to type “C” voltage sag with $h=0.05$, 50% stator voltage compensation and $r_1 = \infty$. 
Figure 5-23. Simulation response of a 2 MW DFIG wind turbine to type “C” voltage sag with $h=0.05$, 50% stator voltage compensation and $\tau_f = 0.1s$. 
Figure 5-24. Simulation response of a 2 MW DFIG wind turbine to type “D” voltage sag with $h=0.05$, 50% stator voltage compensation and $\tau_1 = 0.1$s.
Figure 5-25. Simulation response of a 2 MW DFIG wind turbine to type “G” voltage sag with $h=0.05$, 100% stator voltage compensation and $\tau_1 = \infty$. 
Figure 5-26. Simulation response of a 2 MW DFIG wind turbine to type “G” voltage sag with \( h=0.05 \), 50\% stator voltage compensation and \( \tau_1 = \infty \).
Figure 5-27. Simulation response of a 2 MW DFIG wind turbine to type "G" voltage sag with $h=0.05$, 50% stator voltage compensation and $\tau_1 = 0.1$ s.
6.2 Hardware Demonstration

In order to validate the analytical and simulation analyses, an experimental setup was built and tested. The block diagram of the test setup is shown in Figure 5-28. A picture of the test setup in the lab is also shown in Figure 5-29. It includes the following components:

- A dSPACE DS1104 DSP controller board. The control program is written in Simulink environment combined with the real-time interface of the DS1104 board.
- A DC motor driving the induction motor at desired speed.
- A voltage source inverter (VSI) operating at 40 kHz switching frequency connected to the series transformer. This VSI is used to control the amplitude and the phase of the injected voltage.
- A one horsepower wound rotor induction machine simulating a wind turbine.
- A three-phase transformer (240V:240V) for series voltage injection.
- Sensors for grid voltage, short circuit indicator, rotor currents and stator voltage.

The phase voltages of the grid side is sensed and fed to a phase lock loop (PLL) implemented in the controller to generate the reference voltages. The actual grid voltage and reference voltages are compared to generate the reference voltage and gate commands for the series converter. The output voltage of the converter is applied to the stator side using three single-phase transformers. This configuration allows for independent compensation of phase voltages. Inductor $L_i$ and capacitor $C_i$ form a low
pass filter to remove the switching frequency harmonics from the output of the converter.

The controller also adjusts the voltage of the DC bus capacitor with very slow dynamic.

Figure 5-28. Schematic of DFIG wind turbine with series grid side converter connected via series injection transformer for the proposed LVRT solution.

Figure 5-29. Hardware setup in the lab for testing.
6.2.1 Behavior under Symmetrical Short Circuit without Voltage Compensation

Figure 5-30 shows the measured grid voltage, short circuit indicator, rotor current and stator voltage. The experimental results show that the rotor current jumps to approximately five times of the nominal current during short circuit and exponentially decays to zero with the stator time constant.

![Figure 5-30. System behavior during the short circuit without compensation.](TEK0033.BMP)

6.2.2 Behavior under Symmetrical Short Circuit with Series Voltage Compensation

In this section, the rotor current behavior is analyzed under different conditions for the injected voltage as follows:

b) 100% stator voltage compensation with non-decaying injected voltage.

Figure 5-31 shows the system behavior during the short circuit with full stator voltage compensation. It shows that the short circuit dose not have any significant impact on the rotor current. The rotor current stays within its normal value with small transient due to delay in voltage injection.
Figure 5-31. System behavior during the short circuit with $\tau_i = \infty$.

b) 100% stator voltage compensation with decaying voltage with time constant $\tau_i$.

The results of this case for two values of $\tau_i$ are shown in Figures 5-32 and 5-33. It can be seen that the rotor current decreases exponentially according to the compensated voltage time constant of $\tau_i$. The rotor current starts decaying after the short circuit from its initial value without experiencing any over current.

Figure 5-32. System behavior during the short circuit with $\tau_i = 0.1s$. 
6.2.3 Behavior under Symmetrical Short Circuit with partial Series Voltage Compensation

Since the energy that is being delivered during the short circuit is proportional to the stator voltage, the required size of the energy storage capacitor is decreased due to a smaller stator voltage. In fact, it is not necessary to compensate 100% of the stator voltage during the short circuit to eliminate the rotor circuit over current. The most important point is to keep the frequency of the exponentially decaying compensated voltage the same as the grid frequency during the short circuit. This allows for the stator flux to rotate with its initial speed during the short circuit and results in keeping the rotor circuit voltage due to the stator flux the same as its value during normal operation.

In this section, the rotor current behavior is analyzed under different conditions for the injected voltage as follows:

b) 50% stator voltage compensation with non-decaying injected voltage.
Figure 5-34 shows the system behavior during symmetrical three phase short circuit with 50% series voltage compensation. It shows that the short circuit does not have any significant impact on the rotor current. The non-significant impact on the rotor current in this case is due to the time at which the short circuit is applied.

b) 50% stator voltage compensation with decaying voltage with time constant $\tau_i$.

The results of this case for two values of $\tau_i$ are shown in Figures 5-35 and figure 5-36. It can be seen that the rotor current has some transient and increased by approximately 1p.u. from its value at the moment of the short circuit and then decreases exponentially according to the compensated voltage time constant of $\tau_i$. Again the value of the current at the moment of the short circuit depends at the time at which the short circuit is applied.
Figure 5-35. System behavior during the short circuit with 50% stator voltage compensation and $\tau_1 = 0.05s$.

Figure 5-36. System behavior during the short circuit with 50% stator voltage compensation and $\tau_1 = 0.1s$. 
Chapter 7 Conclusions and Future Work

7.1 Conclusions

DFIG is subject to intense stress during considerable grid voltage sag. Additional measures must be taken to protect the turbine and provide LVRT even at zero grid voltage in accordance with utility requirements. Wind turbine equipped with series voltage compensator described in this thesis is able to stay connected to the grid and limit the rotor currents within an acceptable range. This LVRT solution for the DFIG also allows for reactive power support to the grid during grid fault. The aim of the proposed technique is to limit the rotor side converter high currents and to provide the stator circuit with the necessarily voltage via a series transformer without disconnecting the converter from the rotor or from the grid. The wind turbine can resume normal operation within a few hundred milliseconds after the fault has been cleared. For longer voltage dips, the generator can even supply reactive power to the grid. Simulation and experimental results verify the effectiveness and viability of the proposed technique. According to analyses presented, the size of the energy storage capacitor does not need to be excessively large for the system to operate.

Chapter 1 presents a background of wind turbine technology for utility application, system components and energy capture. The four most common wind turbine types are described.
The most recent grid connection requirements and grid code are summarized in chapter 2. The types of voltage sag and LVRT properties as well as the LVRT requirements are presented.

The space vector quantities and reference frame transformation is described and a dynamic model for DFIG is developed in Chapter 2. Steady state power flow and reactive power analysis are described.

In chapter 4, the effect of grid faults are presented. DFIG rotor voltage under normal and different type of voltage sags is analyzed. System simulation for different type of voltage sages is generated in support of the analytical analysis.

Chapter 5 introduces the use of series grid side converter (SGSC) technique and a control strategy for the SGSC is developed for balanced voltage sages. The balanced sag response control strategy is extended to the more general case of balanced or unbalanced sags. Thy exited solutions for LVRT are discussed in this chapter.

The principle of ride through, sag detection and controller are described in chapter 6.

Operation is demonstrated through simulation and confirmed by experimental results from laboratory scale prototype hardware.
7.2 Summary of Contributions

1. Mathematical evaluation for the effect of grid fault on DFIG by developing a transient model. System analysis under normal and grid fault operations to determine the main source of rotor current rising during grid fault.

2. Introduce the use of series voltage converter to mitigate the undesirable effect of grid fault on the DFIG. Series transformer is augmented in the stator side to eliminate the undesirable behavior of the stator flux during grid fault.

3. Introduce a solution to minimize the size of energy storage required for the voltage ride through. Keeping the stator flux rotating at its initial speed at the moment of the grid fault is the key solution for minimizing the rotor current.

4. Introduce a solution to minimize the KVA rating of the energy storage system. The minimum requirement of the injected voltage is defined.

5. Develop a digital controller to achieve robust voltage injection and ability to response to different types of voltage sages.

6. A laboratory scale prototype to test and validate the proposed solution with the use of digital controller for voltage injection.

7.3 Future Work

7.3.1 Wind Farm Model Refinement

A more accurate model of the farm collector system will enable a more realistic test case for the evaluation of the SGSC. A representative wind farm collection feeder network may include the collection transformers and a short transmission line model which may result in less stressful voltage conditions at the wind turbine terminals.
Second, the model of the mechanical system as a lumped mass may be insufficient, especially when attempting to quantify the effect of transients on gearbox loading.

7.3.2 SCR Bypass of SGSC

The presence of the SGSC during normal operation of the DFIG is undesirable due to the conduction in the inverter and the ohmic losses in the inductor and transformer. Thus it may be desirable to bypass the SGSC with a static SCR switch, and transition to SGSC control during sag events.

7.3.3 Full Scale Hardware Demonstration

The hardware results presented in Chapter 6 are limited in usefulness by the relatively small power rating of the equipment, and the use of an inverter for generating sag events. A full scale hardware demonstration is necessary to study the transient and parasitic effects that may impact the response of the larger and electrically stiffer utility scale wind turbines. Beyond this a full scale demonstration is necessary to study the response to faults within the converter, machine and control system, and develop mitigation measures, if necessary.


Appendix A: Model Parameters

Table A-1: Simulation and Experimental Parameters

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th>Experimental Setup Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratings: $S_n = 1.5$ MW, $f_n = 50$ Hz, $U_n = 690$ V (line–line, rms), 6 pole, PF = 0.9</td>
<td>Ratings: 1hp, 230V, 4 poles, 50Hz, 5A.</td>
</tr>
<tr>
<td>Stator resistance: $R_S = 0.03$ Ohms.</td>
<td>Stator resistance: $R_S = 2.715$ Ohms.</td>
</tr>
<tr>
<td>Stator leakage inductance: $L_{ls} = 59$ mH.</td>
<td>Stator leakage inductance: $L_{ls} = 11.1$ mH.</td>
</tr>
<tr>
<td>Rotor resistance (referred to the stator): $R_r' = 0.022$ Ohms.</td>
<td>Rotor resistance: $R_r = 1.421$ Ohms.</td>
</tr>
<tr>
<td>Rotor leakage inductance (referred to the stator): $L_{lr}' = 59$ mH.</td>
<td>Rotor leakage inductance: $L_{lr} = 11.1$ mH.</td>
</tr>
<tr>
<td>Magnetizing inductance: $L_m = 0.035$ mH.</td>
<td>Magnetizing inductance: $L_m = 202.5$ mH.</td>
</tr>
<tr>
<td>Series voltage controller parameters: $K_p = 20$, $K_i = 5$.</td>
<td>Moment of inertia is $J = 0.004$ Kg·m².</td>
</tr>
<tr>
<td>$C_f = 2.7$ μF.</td>
<td>$L_i = 0.5$ mH.</td>
</tr>
</tbody>
</table>
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