SMES BASED EXCITATION SYSTEM FOR DOUBLY-FED INDUCTION GENERATOR IN WIND POWER APPLICATION

A graduate project submitted in partial fulfillment of the requirements
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By

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Abstract

SMES BASED EXCITATION SYSTEM FOR DOUBLY-FED INDUCTION GENERATOR IN WIND POWER GENERATION

by

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Master of Science in Electrical Engineering

The aim of this project is to propose a super conducting Magnetic Energy Storage (SMES) based excitation system for doubly-fed induction generator (DFIG) utilized in the wind power system. This proposed system consists of rotor-side converter, grid-side converter, the D.C chopper and the super-conducting magnet. The Super Conducting Magnet is associated with the D.C side of the rotor and grid-side converters and handles the active power transfer independently. This magnet is characterized with maximum energy storage and fast response towards the fault. With the help of this magnet we can improve the system stability and protection by leveling the wind power fluctuations and quick response to the faults occurred. The performance characteristics of the system are checked using the MATLAB SIMULINK.
CHAPTER 1: INTRODUCTION

With increasing global temperatures and decreasing finite energy sources, using sustainable energy sources is the best option to preserve the earth for future generations. Among them wind power is a successful approach to take care of issues like pollution and energy shortage. For efficient energy transfer from wind many turbines work at different speed utilizing DFIG’s. The system consists of a power electronic converter that alters the speed of the generator with different wind speed. The converter is less expensive as the rating is commonly 25% of aggregated power and speed extent is 33% of synchronous speed.

Despite the fact that the DFIG have great execution, there are a few issues ought to be concerned. The primary issue is the power fluctuation. The second issue is the operation of DFIG when fault occurs. To solve these issues, the energy storage unit is a better approach.

Hence, Super Conducting Magnetic Energy Storage [SMES] is put forward for consideration. With the help of this magnet we can improve system stability and protection by leveling the wind power fluctuations and quick response to the faults occurred. The performance characteristics of the proposed system are verified using the MATLAB SIMULINK.
Fig. 1. The circuit for the proposed system [8]
CHAPTER 2: WIND ENERGY

2.1 Introduction

Wind is formed due to the uneven warming on the surface of earth. It is present in any piece of the world. The common methods of producing energy using finite source like coal and gas are affecting the nature by releasing toxic gases into the nature. As a result of these gases, the green-house effect is formed. So many people are doing research in utilizing renewable energy sources for energy production. Among them wind power is a successful approach to take care of issues like pollution and energy shortage.

![How Wind is Formed](image)

1. The sun shines on land and water.
2. Land heats up faster than water.
3. Warm air over the land rises.
4. Cool air over the water moves in.

Figure 2 Formation of wind [3]

2.2 Sorts of Wind Turbines

Essentially there are two sorts of turbines depending on the kind of rotor utilized. They are:

- Horizontal-hub wind turbines
- Vertical-hub wind turbines
2.3 segments of wind turbine

![Diagram of wind turbine](image)

Fig 3 segments of wind turbine [3]

Anemometer:

It quantifies the speed of wind and sends the information to the controller.

Blades:

The blades will turn when wind occurs, which in turn makes the rotor to rotate

Controller:

Begins and stops the turbine by monitoring the wind speed
Gearbox:

It helps to change the wind energy to mechanical energy. It is the expensive part in the whole turbine.

Generator:

It changes the mechanical energy to electrical energy.

Nacelle:

It is the outer shield for the gear-box generator, controller and brake

2.4 Power from the Wind

The wind that is blown is captured by the blades of the turbine and is transferred to the gear box which acts mechanically. This gear box is connected to the generator which converts the rotational energy to electrical energy. The power of the wind increases with the increase in the height of the turbine because as the altitude increases we get more wind speed. The power of the wind depends on the area of the blade, as the diameter of the blades increases the power of the wind also increases. The power of the wind also depends on velocity of the wind. Hence, the relationship between the mechanical wind power, speed of wind and area of blades and air density is shown below.

\[ P_m = \frac{Kp(\alpha, \beta)dv}{2}W^3 \]
The force coefficient (Cp) is a nonlinear capacity that speaks about the productivity of the wind turbine to change over wind energy into mechanical energy. It is reliant on two variables, the tip speed proportion (TSR) and the pitch edge. The TSR, \( \lambda \), alludes to a proportion of the turbine angular speed over the wind speed. The scientific representation of the TSR is given by eq. The pitch edge, \( \beta \), alludes to the angle of turbine blades are adjusted in regard to its longitudinal axis

\[
\lambda = \frac{R \ \omega_b}{V_w}
\]

Where R=turbine radius
2.4.1 Cp-lambda

This graph is plotted between Cp vs lambda for different values of Beta (0, 5, 10, and 15).

![Graph of Cp-lambda characteristics](image)

Fig 4 Cp-lambda characteristics [3]

2.5 Induction generator

When an A.C supply is given to stator terminals of an induction machine, the magnetic field gets developed in stator which makes the rotor to run. The induction machine needs an external force for excitation whether it is working as a motor or generator. So to start the induction machine we need a capacitor bank which produces a reactive power to start the machine.
The magnetic flux from stator affects currents in the rotor, which additionally delivers an attractive field. In the event when the rotor operates slower than the rate of pivoting flux, the machine demonstrates like an impelling engine. In the event when the rotor is turned quicker, it acts as a generator delivering power at the synchronous speed.

If the rotor is made to rotate at speed more than synchronous then the slip becomes negative which generates a rotor current in the opposite direction. This current produces the magnetic field and make the machine to work as an induction generator.
2.6 characteristics of an induction machine

The slip of an induction machine is illustrated as the difference between the synchronous speed and the operating speed by synchronous speed. If the rotor speed is equal to the magnetic field of stator then the slip becomes zero which implies the torque to become zero. When the rotor speed is less than the magnetic field of the stator then the machine is working as the motor. As you can see in the above figure if the speed is less than synchronous, then it acts as a motor and if it is more than the synchronous speed it is acting as a generator. The induction machine generates useful power even if the rotor speed changes.

Figure 6 Torque vs. Speed graph of Induction Generator [6]
The accompanying figure demonstrates the per-stage identical circuit of the induction machine.

![Induction Machine Circuit](image)

Figure 7 the identical circuit of an induction machine [6]

In the above figure the ‘S’ represents stator and ‘r’ represents rotor of the machine. ‘m’ represents the magnetizing component.

2.7 Advantages of using the wind power

- Using the wind turbine we can make our atmosphere pollution free from toxic gases which are harm for us.
- The source for the wind power system is free.
- They occupy very less space when compared with other power systems.
- When consolidated with sun oriented power, this vitality source is extraordinary for created and creating nations to give an enduring, dependable supply of power.
Chapter 3: SUPER CONDUCTING MAGNETIC ENERGY STORAGE (SMES)

3.1 Principle of super conducting magnet

In a general inductor the energy stored gets disappeared gradually because of the ohmic resistance present in the conductor. So, to reduce the ohmic resistance to almost a zero value we need to lower the temperature of conductors. The condition for super conducting wire is that the conductor should be worked under the critical temperature and the magnetic field. In a super conductivity wire the resistance is zero which makes the time constant of the material go to infinity.

Generally, liquid helium is utilized to make the conductor super conducting. Because of its heavy size and shape of the high temperature super conductors we need to spend more money when compared with low temperature super conductors. Hence, we prefer low temperature superconductors. The general material we utilize to make low super conductor is Niobium-Titanium (Nb/Ti).

Since, we need to cool the conductor to less than critical temperature it becomes a drawback for this energy storage device. Because it makes the system more complicate by adding the refrigerator and coolant to decrease the temperature. But the efficiency produced by this energy storage device is higher than the other energy storage devices .The explanation behind the high productivity is that there is no compelling reason to change over the energy between distinctive systems like from mechanical to electrical.

3.2 Characteristics of SMES devices

• retaining and conveying a lot of power.

• High productivity.
• Life-time is large.

• Quick reacting time.

• Less maintenance.

• Storage of energy

![Discharge time for various storage devices](image)

Figure 8 Discharge time for various storage devices [6]

3.3 components of a SMES based system

The components of a super conducting energy storage magnet are

• Refrigeration system

• Super conducting coils

• Utility system

• Power converter

• Control
3.3.1 Super conducting coil

The super conducting coil is the crucial part of the entire system, it stores the energy in the magnetic field produce by a flowing current. The energy stored is decided by:
• Size of the loop which decides the inductance of the loop. The bigger the loop, the more prominent put away energy.

• Features of the conductor which decides the greatest current.

Many of the super conductors utilize niobium and titanium (Nb-Ti) as the conducting material. The temperature we need to maintain of this material is 4.2k.

3.3.2 Cryogenic Refrigerator

In order to maintain less temperature for super conductivity. We need a refrigerator to get the required temperature. Generally we are using niobium and titanium (Nb-Ti) as conducting material. So the temperature should be maintained at 4.2k.

To maintain this temperature we are utilizing the refrigerator with helium as the coolant, since it is the only material available in liquid form.

3.3.3 Power switching System

The power switching system has two main objectives.

• One is to change the electric power from D.C to A.C

• The other is to charge and discharge the coil
3.3.4 Control System:

The main task of the control system is to receive the data on power requirements from the grid and send it to the SMES coil. It also monitors the situation of the SMES coil, refrigerator and other parts used in the system. It secures the system and maintains safety. As you can see in the above figure, the controller is monitoring the entire system.

Figure 11 Schematic of the components of SMES system [8]

Figure 12 super conducting energy storage device [7]
The energy stored in the device is defined as:

\[ Ec = \frac{1}{2} LI^2 \]

3.4 Applications:

Because of its high power storage, it is very suitable for industrial applications. It protects the apparatus utilized in the industry from voltage dip and stabilizes the ripples caused. Utilizing high energy because of the refrigerator in this system it is not used in our daily life.

3.5 Disadvantages:

The main drawback of the system is to maintain the temperature. If we fail to maintain the required temperature the SMES starts losing the energy.
Chapter 4: Double-fed induction generator

4.1 Introduction

The DFIG is an induction machine with a wound rotor where the stator and rotor both are joined with electrical sources, hence the term ‘doubly-fed’ is sustained. Now-a-days numerous number of people are utilizing the DFIG in the wind turbines because of its unique application in the wind system. The rotor of the generator is capable to work at different rotational speed. In this type of induction generator, the stator is straight forwardly associated with the grid while rotor winding is joined by means of slip-ring to a back-to-back converter. The converter is less expensive and utilizes only 25% of the aggregated system power.

![Figure 13 Doubly-fed induction generator [1]](image)

4.2 Operation

The rotor windings of the generator which are joined with the converter are stimulated by rotor currents which in turn produces the magnetic field. The magnetic field that is formed in the rotor connects with the stator magnetic field and creates torque. The per-unit circuit is used to discuss more about the torque control in DFIG.
As you can see in the figure the left side is the stator which has two components resistance and the inductance. The magnetizing inductance $L_m$ produces the useful flux in the machine. Similarly, the rotor has also two components the resistance and inductance. The rotor produces the mechanical power by adding the resistance component $R_r \frac{(1-S)}{S}$.

The slip of the machine is illustrated as:

$$ S = \frac{K_s - K_r}{K_s} $$

$K_s$ = synchronous speed,

$K_r$ = mechanical speed of rotor

$$ K_s = \frac{60e}{P} $$

$P$= number of poles; $e$= frequency of the stator

The mechanical torque generated is defined by finding the mechanical power. Where

$$ \text{mechanical power} = 3I_r^2 \left( \frac{1 - s}{s} \right) R_r $$
Therefore, we know the torque is defined by

\[
T_{\text{mech}} = 3I_{r}^{2}\left(\frac{1 - s}{s}\right) \frac{R_{r1}}{\omega_{m}}
\]

\[
\omega_{m} = \frac{(1 - s)\omega_{m}}{k} \quad \text{And} \quad \psi_{m} = \frac{I_{r1}R_{r1}}{S_{s0}}
\]

\[
T_{\text{mech}} = 3p\psi_{m}I_{r1}
\]

4.3 Rotor power converters

The A.C-D.C-A.C converter utilized for the generator comprises of rotor-side converter and grid-side converter which are joined “consecutive”. The main task of the rotor-side converter is to control speed, torque and power factor. While the purpose of the grid-side converter is to maintain the voltage magnitude constant.

![DFIG with RSC and GSC][1]

Figure 15 DFIG with RSC and GSC [1]
To reduce the power error we utilized an external control circle. The rotor current actual is compared with the reference rotor current from the regulator and error is minimized to zero with the help of regulator

4.4 Applications

- The results from this sort of induction generator is greater when compared with other type of generators.
- Wind energy consumed by this generator is more.
- It shows a reliable gear system
- They produce high productive power from the system
- It saves cost from investing on full-rated power converters
Chapter 5 MODELLING OF THE PROPOSED EXCITATION SYSTEM

5.1 System configuration

The system is made out of rotor-side converter, grid-side converter, the d.c chopper and the super conducting magnet. The DFIG is equipped with an electronic converter which can alter the generator speed. The converter is associated with the rotor windings and the super conducting magnet is joined to the D.C side of the two converters which exchanges the active and reactive power autonomously. The super conducting magnet must be characterized with quick response to fault, energy storage which helps to enhance the system steadiness and dependability.

Figure 16 Block diagram wind power system with DFIG and super conducting coil [8]
5.2 controlling of the system

The basic system control is to check the data from the wind turbine which helps to decide the power required for the rotor and grid. When the fault occurs in the system the main objective is to smoothen ripples caused due to the fault.

The next level is to control the grid-side converter, rotor-side converter and the D.C chopper. The pulse width modulated converter and vector control method are utilized to enhance the dynamic power response. The simplified diagram for the control of converters is shown in the below figure

5.2.1 Rotor-side vector control

To reduce the power error we utilized at an external control circle. The rotor current actual is differentiated with the base rotor current from the regulator and error is minimized to zero with the help of regulator.

Figure 17 block diagram to control the system [8]
\[
V_s = I_s \cdot R_s + \frac{d\alpha}{dt}
\]
\[
V_r = I_r \cdot R_r + \frac{d\alpha}{dt}
\]

Where \(V_s\) is stator voltage by grid and \(V_r\) is voltage in the rotor

\[
\alpha_s = L_s \cdot i_s + L_m \cdot i_r
\]

\[
\alpha_r = L_m \cdot i_s + L_r \cdot i_r
\]

The stator and rotor self- inductances are:

\[
L_s = L_m + L_{ls}
\]

\[
L_r = L_m + L_{lr}
\]

Defining the leakage factor

\[
\sigma = 1 - \frac{Lm^2}{Lr} \cdot L
\]

\[
L0 = \frac{Lm^2}{Ls}
\]

\[
V_{rd} = I_{rd} \cdot R_r + \sigma L_r \cdot \frac{d_{ird}}{dt - W_{slip}} \cdot \sigma L_r \cdot i_{rq}
\]

\[
V_{rq} = i_{rq} \cdot R_r + \sigma L_r \cdot \frac{d_{irq}}{dt - W_{slip}} (\sigma L_r \cdot i_{rq} + L0 \cdot I_{ms})
\]

\[
W_{slip} = W_s - W_r
\]

The stator flux angle are calculated from

\[
\alpha_{st} = \int (V_{st} - i_s \cdot R_s)dt
\]

\[
\alpha_{sb} = \int (V_{sb} - i_s \cdot R_s)dt
\]

\[
\theta_s = \tan^{-1}\left(\frac{\alpha_{st}}{\alpha_{sb}}\right)
\]
Figure 18 schematic diagram of rotor-side converter having two PI controllers [9]

5.2.2 Grid-side vector control

Figure 19 simplified figure of grid-side vector control [9]
5.2.3 D.C chopper control

Figure 20 Block diagram of D.C chopper [8]

The DC chopper has two working modes.

- When the gate G1 is turned ON always and the gate G2 is turned ON and OFF simultaneously, then it is in continuous mode.

- When the gate G1 turns off at all times and G2 is turned ON and OFF it becomes discontinuous mode.

When the chopper is in charging state

\[ C \frac{dv}{dt} = -D_{isc} + i_{dc} \]

When the chopper is in discharging state

\[ C \frac{dv}{dt} = (1-D)i_{sc} + i_{dc} \]
5.3 Functions of the excitation system

This excitation system for generator can fulfill the following accomplishments:

- The converters utilized in this system are generally autonomous. This results to enhance the system steadiness and dependability.
- When the over-current flows in the system, it can be stifled utilizing the energy storage capability.
- There is no need for the power conversion from one form to another.
Chapter 6 MATLAB SIMULATION

The figure shown below is the DFIG system without SMES unit

Figure 21 DFIG system without having SMES unit

Figure 22 Control strategy for the rotor-side converter
Figure 23 Control strategy for the grid-side converter

Figure 24 DFIG with super conducting magnetic energy storage device
Figure 25 Control strategy for the chopper

Figure 26 values for the designed simulation [8]

<table>
<thead>
<tr>
<th>Elements</th>
<th>Rating Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFIG</td>
<td></td>
</tr>
<tr>
<td>Rating Power</td>
<td>75 KW</td>
</tr>
<tr>
<td>Rating Voltage</td>
<td>380 V</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>4 mH</td>
</tr>
<tr>
<td>Rotor Leakage inductance</td>
<td>2 mH</td>
</tr>
<tr>
<td>Mutual Inductance</td>
<td>69.31 mH</td>
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<td>Rotor- side convertor</td>
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<td>Rating power</td>
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<tr>
<td>Switching frequency</td>
<td>5 KHz</td>
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<tr>
<td>Grid side convertor</td>
<td></td>
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<tr>
<td>Rating power</td>
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<tr>
<td>Filter Inductance</td>
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<tr>
<td>Switching frequency</td>
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<tr>
<td>DC Chopper</td>
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<td>DC Link Capacitor</td>
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</tr>
<tr>
<td>DC Rating Voltage</td>
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</tr>
</tbody>
</table>
Chapter 7 SIMULATION RESULTS

Figure 27 Stator current of DFIG

Figure 28 Power wave form in the stator
Figure 29 Current in the rotor of DFIG system

Figure 30 Voltage in the rotor of DFIG system
Figure 31 Active power on A.C side of the grid-side converter

Figure 32 Reactive power of the grid-side converter
Figure 33 current in the grid-side converter

Figure 34 Line voltage of the grid-side converter
Figure 35 speed of the wind

Figure 36 output Power from the system
Figure 37 Grid-side power with SMES in the system

Figure 38 Grid-side power without SMES in the system
Chapter 8 Conclusion

In this report we have explained about SMES based double-fed induction generator operation and its use in wind power applications. The converter utilized in this system helps to enhance the system protection and power quality. To verify the proposed circuit we designed a simulation for the system and observed the results. The model is designed with a DFIG wind turbine, converters with their related controllers, and a D.C chopper with a super conducting magnet. The values for this simulation is shown in the above figure26. The figures 27,28,29,30 demonstrates the stator and rotor waveforms of DFIG.

The results from the above figures 31,32,33,34 demonstrates the waveforms of grid-side converter and explains how the SMES can react rapidly with the power requirements.

The results from the above figures 37,38 distinguishes the difference between the system with SMES coil and system without the SMES coil and also explains how the power ripples are smoothen utilizing the super conducting magnet.

So, finally the results demonstrated that the excitation system can react rapidly toward the fault which increases the system protection. We also observed that the power ripples are smoothen viably which enhances the power quality from the system.
REFERENCES


