Superconducting Magnetic Energy Storage (SMES) in Power Systems with Renewable Energy Sources

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Abstract—A power conditioning system consisting of a Superconducting Magnetic Energy Storage (SMES) which can be used to smooth out differences between output power of a generator and power loads is analyzed in this paper. The SMES is connected in shunt with the distribution lines through a converter. The converter is a voltage source converter type with a DC-chopper. The system is controlled by three regulators; they are working on the DC-link voltage, the power to and from the SMES and the AC-currents in the inverter. The regulators controlling the power flow and the AC-currents are cascaded and the DC-link voltage controller is situated in an independent loop with its voltage kept constant using the SMES. Simulations have been carried out using the software PSCAD/EMTDC.

Index Terms—Energy storage, SMES, AC-DC/DC-DC converter, PSCAD.

I. INTRODUCTION

RENEWABLE energy sources will have a key role in supplying energy in the future. More exactly wind power and other types of new renewables. There are several issues regarding large scale integration of new renewables into the power system. One of the problems is the security of supply. It is not possible to control the power output from a wind park, or the output from a wave energy power plant as it is for hydropower. These energy sources will provide energy, or not provide, independent of the demand. The output power can also have relatively large variations within a short time span. A solution to this problem is the concept of energy storage, and there are several different concepts. Fig. 1 shows some of the different concepts and their characteristics with regards to power output and output duration. The different storage types can principally be divided into two groups. There are devices which can store large amounts of energy, but do not react so fast. Pumped hydro storage is one energy storage solution of this type. In the other end there are fast acting devices which store smaller amounts of energy. Superconducting Magnetic Energy Storage (SMES) is placed in this group. The SMES is a coil which is in a superconducting state at cryogenic temperature. This means that the ohmic losses during operation will be very low, close to zero. An energy storage system of this type can charge and discharge very fast, or said in a different way it has the ability to absorb, or deliver high quantities of power. Another positive element about SMES is the life cycle. A coil of this type can withstand tens of thousands of charging cycles. This corresponds to several decades of operation, and compared to battery storage systems the lifetime is much longer [1]. To reach the superconducting state the coil has to be cooled to less than 9.8 K [2]. This is achieved using liquid helium which brings the temperature down to 4.2 K. The need for cooling is an aspect which lowers the efficiency, but the power needed for cooling is far less than the output power of the SMES [3]. Combined with ohmic losses in the non superconducting devices the efficiency can exceed 90% [4].

When deciding which converter topology to use to connect the SMES to the grid, aspects as harmonic distortion, usage of reactive power and on-state losses has to be considered. A line commutated converter using thyristors has low on-state losses and it can handle large amounts of power, but it has lagging power factor, and high low order harmonics. Even the twelve pulse topology has too high total harmonic distortion.
II. THE SYSTEM TOPOLOGY

The topology of the system which is being studied is shown in Fig. 2. It consists of an induction generator with a rated power of 2 MW. This is connected to a grid through a step-up transformer (T1) with ratio 0.69/22 kV. The system has a constant pure active load of 0.5 MW per phase. In order to magnetize the induction generator a main grid is also connected. The SMES coil is connected in shunt with the lines through a transformer (T2), which is equal to T1. The converter is a VSC and a DC chopper connected via a DC-link. The SMES is connected at the output terminals of the DC chopper. The inductance of the coil is 1.8 H. The base frequency in the system is 50 Hz.

A. The DC-DC converter

The DC-DC converter which has been used is the chopper shown in Fig. 3 [8]. This converter has been studied using the software PSIM and PSCAD/EMTDC. The two switches \( T_A \) and \( T_B \) are modeled as fairly ideal IGBTs having a ON-resistance of 0.001 \( \Omega \), OFF-resistance of \( 10^6 \) \( \Omega \). These switches are controlled using PWM switching technique. The two switches are controlled by the same function, and are both ON or OFF at the same time. The control of the IGBTs is achieved by comparison of a DC control voltage, \( V_{\text{con}} \) and a triangular voltage \( V_{\text{tri}} \). \( V_{\text{tri}} \) has a minimum value of -1.0 and a maximum value of +1.0. The following describes the relationship between \( V_{\text{con}} \) and \( V_{\text{tri}} \):

\[
m_a = \frac{V_{\text{con}}}{V_{\text{tri}}} \tag{1}
\]

\( m_a \) can attain values between -1 and +1. The following explains the behaviour of \( T_A \) and \( T_B \):

\[
V_{\text{tri}} < V_{\text{con}} \rightarrow T_A \text{ and } T_B \text{ are ON} \\
V_{\text{tri}} > V_{\text{con}} \rightarrow T_A \text{ and } T_B \text{ are OFF}
\]

As can be seen from Fig. 3 the voltage across the coil \( V_L \) will switch between \( \pm V_{\text{dc}} \). The relation:

\[
V_L = L \frac{di}{dt} \tag{2}
\]

shows that when the IGBTs are ON, and the voltage across the inductor is \( \pm V_{\text{dc}} \), the current in the coil will increase. When the IGBTs are OFF, \( V_L \) will be equal to \( -V_{\text{dc}} \), and the current in the coil will decrease. There is also a third state, which is steady state, or stand by. This state is when the current in the coil is constant. These three states can be described using \( m_a \):

\[
\begin{align*}
&m_a > 0 : \text{The coil will be in the charge state.} \\
&m_a < 0 : \text{The coil will be in the discharge state.} \\
&m_a = 0 : \text{The coil will be in steady state.}
\end{align*}
\]

During the different states the current will not have a completely constant increase or decrease. But on average it will increase when \( m_a \) is greater than zero and decrease when it is less than zero. In steady state mode the charge period of the coil will be equal to the discharge period, and the current will fluctuate around a certain value. Fig. 4 shows how the current increase and decrease, but increase on average during several switching periods. For comparison and exemplification \( m_a \) has
been set equal to 0.4 and 0.8, and the carrier signal has been given a frequency of 2 Hz and amplitude of ±0.5. The larger the absolute value of \( m_a \), the smaller is the current derivative in the opposite direction than the average current derivative as can be seen from Fig. 4. The higher the switching frequency is, the smaller is the current flow in the opposite direction than the average current direction in each switching interval.

In a real case simulation the charging and the discharging of the coil will have to be automatic. The control techniques will be described later in this text.

B. AC-DC converter

The AC-DC converter is a conventional six switch full bridge converter shown in Fig. 5. This means that the converter can act as a rectifier and inverter. A capacitor is connected in shunt between the two converters in the DC-link. The capacitor is connected in order to keep the DC-voltage on a constant level. The switching devices are IGBTs having the same properties as those in the DC-DC converter. The DC-side of the converter is connected to the terminals of the DC-chopper. The switching is controlled using a PWM-switching scheme, comparing a high frequency triangular signal and a voltage reference signal. The reference signal is made using \( d-q \) transformation. The \( d-q \) transformation secures simpler calculation in the control loops because of the reduction from three AC quantities to two DC quantities. It also enables the possibility to control active and reactive power independent from each other [9].

III. CONTROL SYSTEM

The control system consists of three regulators. A DC-link voltage controller, an active power controller and a current controller. See appendix for block diagram and parameters of the regulators. The parameters has been calculated using the modulus optimum tuning criterion for the inner current controller, and the symmetric optimum tuning criterion for the other two regulators. The DC-link voltage regulator is aimed at keeping the DC-link voltage on a constant reference. This regulator is a PI-regulator (proportional-integral). The reference voltage is set to be equal to 1.0pu, which equals 1.1 kV. The output of the regulator gives the voltage reference for the DC-chopper, which is compared with a triangular voltage. This means that the superconducting coil is being charged or discharged to keep the voltage in the DC-link on a constant level, or said in another way keep the current in the DC-link capacitor near zero. This secures that the control of the charging of the coil will be fast and accurate as the control structure consists of only one block.

The control of the AC-DC converter is composed by two cascaded regulators. The outer controller is the active power controller. The reference for this regulator is the difference between the generated power from the induction generator and the active power demand by the load. The error is passed through a PI-regulator and gives a reference current \( i_{dc,ref} \). This reference goes into the inner current controller which output is the voltage reference for the PWM. The output of the PWM is the triggering signals for the IGBTs in the converter.

IV. SIMULATIONS

The power system in Fig. 2 has been simulated using the software PSCAD/EMTDC. Simulations with different inductance values have been performed. The inductance values are: 0.18 H, 1.8 H and 12 H. The sequence of events in the simulation are given in Table I. This line of events takes the SMES through all the three different states. The negative sign before the torque reference indicates that it is driven as a generator. -1.0pu corresponds to rated power, which is 2 MW. This leaves 0.5 MW of extra power because the total load is only 1.5 MW. The extra power is used to charge the coil. When the torque reference is reduced to 0.75pu, the generated power is equal to the load power, and the SMES is in steady state, drawing no power nor supplying power to the network. As the torque reference drops to 0.6pu the power from the generator is not large enough to supply the loads. This takes the SMES into the discharging state, which means that it

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>System start up, generator control mode set to torque control, and torque reference set to -1.0pu</td>
</tr>
<tr>
<td>2.0</td>
<td>Generator torque reference set to -0.75pu</td>
</tr>
<tr>
<td>4.0</td>
<td>Generator torque reference set to -0.6pu</td>
</tr>
<tr>
<td>6.0</td>
<td>Simulation stops</td>
</tr>
</tbody>
</table>
supplies power to the grid. For comparison the simulation has also been carried out when the SMES is not connected to the grid. Fig. 6 shows the power output from the induction generator. The first 0.2 second is the generator start-up period, this results in some transients, but these have not been given any consideration. As can be seen the power output does not change instantaneously due to inertia in the generator. It is also clear that 75% torque reference does not completely comply with 75% power output from the generator.

The power flow in the SMES (grey line) is shown in Fig. 7 together with the difference between the generated power and the load (black line). This difference is the reference for the SMES power. The plot shows that the power to and from the SMES follows the reference very good for these operating conditions. As aforesaid the first 0.2 second is the start-up period of the generator. During this period the reference power for the SMES is set to zero to avoid the controller from trying to follow the difference between generated power and the load under transitory conditions.

The current and the energy in the superconducting coil during the same sequence of simulation is shown in Fig. 8 and Fig. 9 for the three different inductance values. The relation between current and energy is:

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

(3)

The different current values and energy levels can be found in Table II. The maximum current level in the coil with the least inductance is much higher than the current levels of the coils having larger inductance. But the energy level is as seen lower. The low inductance coil does also lose more of its stored energy during the steady state than the others. The reason for the more varying current is given by Lenz’s law [10] which says that there will be induced an emf to oppose the change of current. This opposing emf is stronger in a coil having more inductance, and thereby the coil having the least inductance will experience more change in the current. An advantage of the low inductance coil is that it can react quicker on demands from the network. On the other side is the large inductance coil which stores more energy, but have a somewhat slower reaction time. Anyway the response time is very short, so this is not a major issue. The low current in the 12 H-coil can be an advantage when it comes to equipment. It would mean less demand on the current handling capabilities of non superconducting components in the system.
The maximum current in the low inductance coil is almost seven times higher than for the high inductance coil. It is also evident that the maximum energy in the 12 H-coil and the 1.8 H-coil are quite similar. The decrease in the current during the steady state period is very large for the 0.18 H-coil and the current decrease is also present for the two others. These losses come from the path the current will have to flow during steady state, and the fact that it is difficult to tune the output from the generator to be exactly similar to the load power and thereby the power reference equal to zero.

Fig. 11 shows the power exchange with the interconnected power grid. It is evident that in the case of no SMES the interconnected network has to absorb or cover the power fluctuations from the generator. The differences between the different inductance cases consist of some fluctuations in the beginning, and a decrease in power at the end of the simulation time for the 12 H-coil. The reason for this power dip is that the current in the coil goes under a certain threshold. In order to deliver the requested power, the DC-link voltage will have to increase beyond its limit. When this does not occur, the power output from the SMES decreases. The DC-link voltage can be increased in order to utilize more of the energy in the coil. However this is outside the scope of this paper. The 12 H-setting has the largest fluctuations in the power exchange. This is due to the longer settling time of the DC-link voltage when the inductance is large.

**V. SIZING OF UNITS IN THE SYSTEM**

The current in the SMES coil is the constraining factor on the switching units. The simulations show that the maximum current is around 1 kA. A current of this magnitude will not make any difficulties regarding the availability of devices. Semiconductors like the ones used in this system can handle up to 2.4 kA [11] when it comes to IGBTs, and currents much higher than this when it comes to diodes. The reference value of the DC-link voltage is 1.1 kV. On the AC side the peak of the line to line voltage is 976 V. Neither the voltage magnitudes make any difficulties when it comes to the availability of devices. An IGBT having a current rating of 2400 A and voltage rating of 1700 V [12] will fulfill the requirements in the operation. It will also introduce safety margins. The constraining factor in the SMES coil is the current. The maximum current is called its critical current. Above this current the coil will lose its superconductivity. Therefore it is important to stay below this limit and include a safety margin [2]. The coil inductance will influence the amount of stored energy, and is a parameter which is determined by the number of turns, the cross sectional area, and the length of the wire [10]. The inductance of the coil in this system has been chosen to be fairly low because the unit is used to compensate power fluctuations and thus the stored energy level is not the highest priority. An inductance of 1.8 H has through simulations proved to be a good choice for this purpose.

**VI. CONCLUSION AND FURTHER WORK**

In this paper a power conditioning system for a SMES coil has been studied for load leveling in a power system with renewable energy sources. The energy storage system has been connected in shunt with the power grid. A comparison between three different inductance values of the SMES-coil has also been performed. From the comparison the 1.8 H-coil proved to be the most suitable. The energy level in this coil was slightly less than for the 12 H-coil, but the large inductance coil was not able to deliver the requested power for the entire simulation. The small inductance coil introduced too high current in the DC-link. The control system of the converter has been divided into two parts. One PI-regulator controlling the DC-voltage with the DC chopper and two cascaded regulators where the outer one is controlling the power flow in the SMES and the inner regulator controls the current in the AC-DC converter. This division ensures a faster reaction time from the controllers than if all the regulators were connected in series. The simulation results show that the SMES will relieve the strain on the connection to the interconnected grid and work as a supplementary power source when the power from the induction generator fluctuates as when coming from wind or wave sources. Further work which can be done involves improving the steady state response of the SMES current. A current source converter topology replacing the voltage source converter topology and DC-chopper will also be investigated. Different connection strategies of the SMES should also be investigated. This includes series compensation instead of shunt compensation and both shunt and series compensation at the same time.
APPENDIX

BLOCK DIAGRAMS FOR THE REGULATORS

![Diagram](image)

Fig. 12. The DC-voltage controller.

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>THE PARAMETERS IN THE DC-VOLTAGE CONTROLLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>$K_{pv,pu}$</td>
<td>63.48</td>
</tr>
<tr>
<td>$T_v$</td>
<td>0.0016</td>
</tr>
<tr>
<td>$T_a$</td>
<td>$T_{switch} = 0.0001$</td>
</tr>
<tr>
<td>$C_{pu}$</td>
<td>100Hz</td>
</tr>
</tbody>
</table>

$\text{Table III}$

![Diagram](image)

Fig. 13. The inner current controller.

<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>THE PARAMETERS IN THE INNER CURRENT CONTROLLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>$K_{pu,pu}$</td>
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<tr>
<td>$T_v$</td>
<td>0.0849</td>
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<tr>
<td>$T_a$</td>
<td>$T_{switch} = 0.0001$</td>
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<tr>
<td>$R_{pu}$</td>
<td>0.00375</td>
</tr>
<tr>
<td>$\tau_{pu}$</td>
<td>0.08488</td>
</tr>
</tbody>
</table>

$\text{Table IV}$

![Diagram](image)

Fig. 14. The outer power controller.

<table>
<thead>
<tr>
<th>TABLE V</th>
<th>THE PARAMETERS IN THE OUTER POWER CONTROLLER</th>
</tr>
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<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
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</tr>
<tr>
<td>$T_p$</td>
<td>0.0002</td>
</tr>
<tr>
<td>$T_{eq}$</td>
<td>$2T_a = 0.0001$</td>
</tr>
<tr>
<td>$R_{pu}$</td>
<td>0.00376</td>
</tr>
<tr>
<td>$v_d$</td>
<td>$\geq 1$</td>
</tr>
</tbody>
</table>

$\text{Table V}$

REFERENCES


