Enhancement Of Fault Ride Through of DFIG Based Wind Energy Conversion System With The Application of SMES

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Abstract--Doubly Fed Induction Generators (DFIGs) find a great deal of application among variable speed wind turbines because of their advantages like operation at variable speed, ability to produce active and reactive power in all the four quadrants, higher efficiency, and extracting maximum electric power at different velocities of wind with the help of speed variation of the rotor and the usage of converters having lower rating and thereby lesser overall cost. Till date DFIG based wind energy conversion systems (WECS) have reached 55% of the total installed wind capacity all over the world. Some of their drawbacks include weak fault ride through capability and high sensitivity to grid disturbances. Earlier wind turbine generators were not kept connected to the power grid during grid faults to avoid their damage. But as per the new grid codes the transmission system they must keep supplying power into the grid during fault. The paper proposes enhancement of the performance characteristics of a doubly fed induction generator with the implementation of SMES unit when voltage sag and swell are observed at the grid side. The proposed SMES configuration has VSC as the rotor side converter and dc-dc chopper as the grid side converter controlled by the hysteresis current control methodology and fuzzy logic rules respectively. MATLAB/SIMULINK software is used to perform simulation. Comparison of the results reveal the effectiveness of the proposed SMES controller in improving the overall performance of the WECS system under study.

Keywords--Doubly Fed Induction Generator, Superconducting Magnetic Energy Storage, Fault Ride Through, Hysteresis Current Control, Fuzzy Logic Control.

I. INTRODUCTION

Pollution caused by conventional energy sources, their depletion and implementation of carbon tax have triggered the renewable energy utilization throughout the world. Renewable energy sources are unpolluted and available in the nature in large amount. Among all other renewable sources, wind has the biggest share of contribution. Earlier wind energy conversion systems used fixed speed turbines and were directly connected to grid.

Development of power electronics led to variable speed WECS and hence enhanced the capture of wind energy along with the reduced impact of transient wind gusts and subsequent fatigue.

The net amount of wind turbines installed in the whole world in the year of 2030 is 573 GW [1].

Power quality issues are considered for new construction or connection of generation systems to the existing ones. This paper shows a thorough analysis of voltage sag and swell ride through capacity of DFIG. A voltage sag can be defined as the drop of 0.1 to 0.9 pu in the rms value of voltage at a power frequency for time durations ranging from a half 5 cycles to a minute. They are caused due to system faults, heavy loads injected in the system, turning on large motors.

On the other hand a swell or rise in voltage swell can be defined as increase in the rms value of the voltage at the power frequency for a time durations ranging from a half cycle to a minute. During voltage swell the magnitude of voltage may lie in the range of 1.1 and 1.8 pu. They are less common than dips. They are observed while disconnection of large load or bringing large capacitor banks into operation. Also in a three phase system the voltage on the healthy phases during a single line to ground fault is more than the faulted phase [2].

Energy storage devices can effectively improve the competitiveness of renewable energy generators but they are very volatile and complicates the operation. This issue can be smoothed through energy storage systems[3] [4]. The time response of energy storage systems depends on the physical principle on which they are based[3]. The paper discusses the operation of an SMES systems to enhance the sag and swell ride through caliber of WECS during voltage sags and swells.

II. LAYOUT OF A DFIG WECS

Fig.1 Typical Configuration Of DFIG Based WECS
The generators used for wind turbine can be subcategorized as fixed or variable speed type wind turbines. DFIG serves as a widely used type of wind turbine which works on the variable wind velocities. It uses a power converter of medium size along with slip rings which are attached to the rotor. At the speed of generator in the range of super-synchronous speed, the electric power is delivered to the grid through both the rotor and the stator. Whereas, at speed less than the synchronous speed the grid supplies power to the rotor. The generator winding located at the stator side is coupled with the grid and the rotor winding to a power electronic converter [6]. A schematic view of the block diagram of a doubly fed induction generator is as per Fig. 1.

This paper analyses a system as depicted in the Fig. 2(A). The output of six DFIGs of rating 1.5 Megawatts is given to a delta transformer which steps up the voltage to 25 kilowatts for further connection with the grid at PCC. An ideal constant frequency 3 phase voltage source is used to represent the grid. The connection of grid has been with the wind generator after a transmission line of length 30 km. To represent a healthy operating state no reactive power is delivered by these generators. The velocity of wind which is experienced at the turbine blades is assumed to be 15 m/s. this wind velocity produces a turbine output power and velocity of generators each equal to 1 per unit. A 25 KV bus is used for interfacing the SMES Unit of maximum capacity of 25 MJ at PCC This unit is assumed to be charged completely[7].

III. SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNITS GENERAL LAYOUT

SMES is used for the storage of energy as magnetic field that is developed inside a coil which is resultant of the current flow inside it. A superconducting material is used for coil. It is kept at a temperature lower than the critical temperature of the material. This can be achieved by immersing it in a preservative like liquid helium within a cryostat which is insulated with the help of vacuum. The coil is discharged to release its stored energy. Fig. 2 indicated the representation of an SMES system.
Inside the SMES coil the energy stored can be calculated with the formula as per equation (1)

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

(1)

In the above equation E is the energy stored in (W-Sec), L is the coil’s inductance in Henrys and I is the direct current flow through coils in Amperes.

IV. SMES CONFIGURATION

The advantages like high power and energy density with more efficiency of storing and releasing energy. The SMES unit has a response of storing the charge which does not depend upon any external parameter and is present in all the values of current and voltage. This characteristic makes SMES more suitable for power system applications than any other energy storage systems. When applied to any typical power system its behaviour is similar to a power source whose active part and reactive part of the power can be varied as per the requirement by the grid [10].

A conventional unit that uses an SMES can be understood as a direct current device which can extract and absorb energy which is developed like a magnetic field. The direct current which circulated within the superconducting wire inside a massive magnetic material gives rise to a magnetic field. The energy which is produced in this manner is stored in the form of circulating current and therefore such type of energy can be easily and instantaneously drawn from an SMES unit. The period of storage or delivery of electrical energy can be as minute as a fraction of second or as large as several hours.

The control technique used for SMES unit comprises of a converter of voltage source type (VSC) and chopper interconnected through a DC link capacitor. Hysteresis current controller (HCC) which can be used to operate the operation of the voltage source converter while the chopper is controlled using a controller which operates on the fuzzy logic rules as implied in the Figure 4.

V. SMES CAPACITY

The power system which is under consideration has below mentioned components:

A doubly fed induction generator which comprises of six 1.5 megawatt generators together resulting in a total power rating of 9 Megawatts. The SMES unit has a rated energy which is assigned a value of 1 MJ. The inductance of the chosen coil is set to be half Henney and therefore its nominal current is opted to be 2 kA [9].

The SMES coil should be operational during the events of voltage sag as well as voltage swells therefore the SMES coil must be assigned with a rated inductor current which has a value level higher than the nominal value of the coil current. Hence the inductor current chosen for SMES coil under consideration is 2 KA. Since SMES is assigned such a higher rating the unit can absorb a maximum energy of up to 1.03 MJ in the event of voltage swells.

The capacity of an SMES unit is decided by its application and the charging/discharging duration. If the unit has a very high energy rating, it will be useful in quicker operation of SMES to damp the oscillations. This might result in an extensively costly unit because of the higher value of current within the coil. On other hand, the amount of energy stored within the unit can be reduced to a lower value and this will be limiting the amount of energy delivered by it during disturbances, and hence it will be inefficient to rapidly control system oscillations.

VI. SMES CONTROL TECHNIQUE

The SMES unit which is analyzed in this research comprises of a voltage source converter along with a dc chopper. Its location within the said system is described in the block diagram shown in Fig. 5. The control operation performed by the voltage source converter block as well as the dc chopper unit are performed by hysteresis type current controller (HCC) and a fuzzy logic control technique (FLC), respectively.

The control technique used in this paper is easier to implement and operate practically. Computation time for system with more number of PI controllers is more which hampers its optimal tuning of the various parameters present within the system and hence it degrades the overall system stability and also affects the dynamic response at the time of transients.
Computational time must be chosen to optimally tune its parameters to maintain overall system stability and to achieve satisfactory dynamic response during transient events. Hence the number of PI controllers used in this technique are reduced to two.

The control technique used for the operation of a dc–dc chopper uses the active power that is generated at the terminals of the DFIG in the form of its control parameter. This technique does not take into account the capability of energy storage of the SMES unit under study. The SMES coil current to take the SMES stored energy capacity into account, along with the DFIG generated power as control parameters to determine the direction and level of power exchange between the SMES coil and the ac system.

A. Hysteresis Current Controller

Because of its advantages like ability to rapidly switch during dynamic conditions, inherent characteristics for limiting the maximum value of the current, it is easier to implement and control practically therefore these controllers are widely used. Typical operation of a hysteresis current controller is demonstrated in fig. 6.

![Fig.6 Phase Hysteresis Current Control Method](image)

Each phase has a reference current value around which there is tolerance band present. The switching signals are generated by investigating the difference between the magnitude of the physical value of the phase current obtained and the value of tolerable magnitude of reference current which is related to that corresponding phase. The control of these band currents is performed by monitoring and controlling their phase voltages and the voltage of the other two phases in the system. Inter phase dependence causes high switching frequencies. Hence the application of phase locked loop methodology is done in order to achieve the operation of the converter as per the desired levels of the frequency [10]. The schematic view of a simplified phase locked loop is as per fig. 7.

![Fig.7 Block Diagram Of Phase Locked Loop](image)

The SMES unit under study is controlled to operate during voltage variations at the grid side by this method. This can achieved with the help of an auxiliary phase locked loop as depicted in the Fig. 8.

![Fig.8. Control Technique For VSC](image)

Hysteresis current control technology is implemented to compare all of the magnitude of three phase practically measured line currents \( I_{abc} \) to their predetermined values. Theses predetermined values are derived by performing a parks transformation of d axis and q axis references currents which can be achieved from the PI controllers which operate on the calculated value of the dc link capacitor voltage and \( V_s \) [11].

B. Fuzzy Logic Controller

Fuzzy logic control technique controls the duty cycle of chopper and hence the power transfer between the SMES coil and the grid. The operational diagram of chopper is as implied in fig. 9.
Development of a fuzzy logic controller is a process of mapping the designated outputs from given inputs. Flow chart of this process is as given in fig. 10.

Input variables to FLC are the active power at the DFIG terminals \( P_g \) and current which is flowing in the SMES coil \( I_{SMES} \). Whereas the fuzzy logic controller generates an result in the form of the duty cycle \( D \) for the chopper. The operation along with the respective input and outputs of the fuzzy logic controller is as indicated in Fig. 11. As shown in [11].

Although PI controller can perform a key role in DFIG to damp the inter-area oscillations, but its better performance is required to meet the suitable range of gains that, is possible with much amount of simulations, while the fuzzy controller scheme is regulated in lesser simulations.

The operating characteristics for the desired operation of the SMES coil to enhance the voltage are as given in Fig 12.

Duty cycle of the chopper is used to decide the amplitude and quadrant of exchange of energy among the SMES unit and the grid. Under normal operating conditions, the duty cycle of the chopper is 0.5 and SMES is kept out of operation. The bypass switch connected parallel to SMES remains closed only for \( D = 0.5 \) otherwise it is opened. When the energy circulated within the grid becomes less, the value of Duty cycle is lowered below 0.5 consequently the energy stored inside the SMES unit is supplied to the grid, whereas if \( D \) is more 0.5 SMES is charged. The relation between \( V_{SMES} \) and \( V_{DC,SMES} \) can be written as

\[
V_{SMES} = (1 - 2D)V_{DC,SMES}
\]

Here, \( V_{SMES} \) indicates the SMES coils terminal voltage, \( D \) denotes the duty cycle of class the chopper, and \( V_{DC,SMES} \) stands for the voltage present in the dc link capacitor. Both the input variables i.e., power generated \( P_g \) and current in SMES coil \( I_{SMES} \) are used to make the fuzzy logic rules in the form of a Gaussian MF as shown in Figs. 13(a) and (b). The resultant membership function depicted in the fig. 13(c) indicated the duty cycle. The variation in SMES current and DFIG output power, is used to develop a set of fuzzy logic rules in the form of if- and then to determine membership function of duty cycle. The surface graph shown in fig 13 can be used to calculate the required value of \( D \).
Fig. 15(i) shows that the results of simulation without SMES have active power obtained from the DFIG drops down to 60% and the highest peak 40% is observed while clearing the fault. But when the SMES unit is present the DFIG output power drops down only till 8.75%. According to fig. 15(ii) in presence of SMES the value of \( Q_g \) generated by the DFIG is lowered during sag conditions. Along with this, the characteristic of \( Q_g \) stabilizes within a shorter time duration than the condition in absence of an SMES unit. Fig. 15(iii) shows the voltage at PCC. Without SMES, the voltage drops to 60% but this can be improved to 80% in presence of the SMES unit. Hence the voltage dip across the DFIG is also reduced within the tolerance limits assigned by the manufacturers. When the energy generated by a DFIG falls, in order to balance this energy, the velocity of the generators is raised. Fig. 15(iv) shows that the rotor accelerates and oscillates in absence of the SMES unit but with SMES the power drop reduces. The magnitude of maximum over shoot and the time to reach steady state is also lowered. The value of \( V_{dc} \) over shoots at the event of clearing the sag or swell. This overshoot is minutely decreased in presence of SMES as depicted in the fig. 15(v). The response at PCC is compared with the fault ride through of Spain.
Fig. 15 characteristics of various parameters of DFIG during voltage dip in presence and absence of an SMES unit.

**B. Comparison of Results With and Without SMES During Voltage Swell**

In the system under consideration, a voltage swell of 1.5 pu starting from t = 2 s is simulated at grid side. It lasts for 0.05 s. Fig. 16(i) shows that real power generated at the DFIG terminals will increase during swell and will be reduced after clearing it.

According to fig. 16(ii) when a voltage rise occurs the DFIG absorbs the excessive amount of apparent power to compensate for the voltage rise. The magnitude of apparent power that the generator absorbs is reduced in presence of an SMES unit. This is because the voltage level at the point of common coupling is improvised to lower than 130% when an SMES unit is connected.

Otherwise it remains above 130%. As per the fig. 16(iii) when the SMES unit is not connected to the system the voltage profile violated the grid codes of Spain and Australia. Hence the DFIG is likely to be removed from the grid if it maintains such a voltage profile.
Fig. 16(iv) shows that shaft speed is minutely enhanced due to the presence of SMES. The magnitude of $V_{dc}$ oscillates significantly without the SMES unit this might reach overshoot level and consequently block the converters. Such oscillations are reduced with SMES unit.

VIII. CONCLUSION

This research paper puts forth a new technique to enhance the transient response of a wind energy conversion system based on doubly fed induction generator during voltage sag and voltage swell conditions. According to the simulation results the SMES unit is highly efficient and practically feasible method to improve the voltage profile and transient characteristics during grid faults. The control technique of SMES unit is sophisticated and its practical implementation is feasible. On the other hand the SMES unit is an expensive equipment but has a promising future in power system field.

REFERENCES


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