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Superconducting magnetic energy storage for stabilizing grid integrated with wind power generation systems

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Abstract Due to interconnection of various renewable energies and adaptive technologies, voltage quality and frequency stability of modern power systems are becoming erratic. Superconducting magnetic energy storage (SMES), for its dynamic characteristic, is very efficient for rapid exchange of electrical power with grid during small and large disturbances to address those instabilities. In addition, SMES plays an important role in integrating renewable sources such as wind generators to power grid by controlling output power of wind plant and improving the stability of power system. Efficient application of SMES in various power system operations depends on the proper location in the power system, exact energy and power ratings and appropriate controllers. In this paper, an effort is given to explain SMES device and its controllability to mitigate the stability of power grid integrated with wind power generation systems.

Keywords Power fluctuation, Power quality, Low voltage ride through, Superconducting magnetic energy storage, Superconductors, Wind energy

1 Introduction

Renewables are infinite sources of power and have long-term certainty over the conventional energy resources. Like other renewables, wind energy is also reducing a significant part of global carbon emissions. As the interests of research and investment on wind generation technology have greatly increased, the cost of this technology is falling and efficiency continues to rise day by day. Due to its inexhaustibility and availability, it provides security of supply, compared to fossil fuels which are concentrated in certain regions [1]. In 2016, wind turbines of 55.6 GW were installed to bring the total installed wind power capacity to 486.8 GW. This avoided over 637 million tons of CO_2 emissions globally. According to the Global Wind Energy Council, the total installed wind power capacity will reach 800 GW by 2021 [2].

The increasing number of integrations in wind energy is also increasing the reliability, quality and stability problems of the electricity grid. New strategies of maintenance and operation are required to improve the power quality. Numerous techniques such as wind forecasting improvement, perfection in wind turbine design and progression in power electronics have been proposed to augment the wind energy penetration. However, only a few have addressed the issues of wind intermittency, grid stability and flexibility at the same time. The wind energy market was initiated with fixed speed (FS) wind power generation systems (WPGSs) in 1990s. FS squirrel cage induction generators (SCIGs) are the most popular wind turbine generators (WTGs) as these have various advantages such as simple and maintenance free operation, cost-effective performance and robustness. However, FS-WPGSs are incapable in tracking maximum wind energy, have low efficiency during rapid fluctuation in wind speed and needs isolation

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during various grid faults. Also, if FS-SCIGs are installed at the distribution line, voltage sag increases with the increase in distribution-line length because of high inrush current at the system interconnection [3]. All the more, since the induction generator absorbs reactive power from the network, parallel capacitors are required to improve the power factor. However, the FS-WPGSs have lifetime of around 20 years and represented around 40% of WPGS installations all over the world [4].

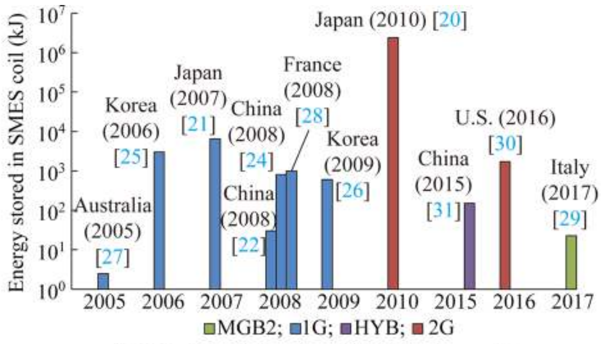
Variable speed (VS) WPGS technology such as the AWT-26 were introduced to the modern wind energy market in 1998 [5] and are dominating the fixed speed SCIG-WTGs. Variable speed wind power generation systems have superior advantages like more captured energy, less mechanical stress and less acoustic noise. Variable speed WPGSs are classified into two types based on their conversion systems; these are WPGS with full scale converters and WPGS with partial scale converters. Permanent magnet synchronous generators (PMSGs) and wound rotor induction generators (WRIGs) are generally used in WPGSs with full scale converters and partial scale converters respectively. The capacity of converters used in WPGSs with partial scale converters or doubly fed induction generators (DFIGs) are one fourth of the rated capacity of the generators, while the speed range of the generators are 33% above or below the synchronous speed [6]. Therefore the converters are much cheaper and this makes them more attractive than FS-WPGSs. However, WPGSs with full capacity power converters have merits of better power quality and higher reliability.

DFIG has many advantages such as small size, low cost, maximum power capturing capability, low converter power rating, high system efficiency and independent active and reactive power control ability. DFIG is connected to the alternating current (AC) network through back to back voltage source converter (VSC) circuit. This converter circuit helps DFIG to facilitate the variable-speed operation during normal condition and helps grid to offer reactive power support during disturbance. The rotor-side converter (RSC) controls the rotor speed and tracks the maximum DFIG generated power to extract more energy from fluctuating wind while the grid-side converter (GSC) controls the voltage level across the direct current (DC) link capacitor by exchanging power with the grid. Power fluctuations during normal operation and low voltage ride through (LVRT) during the occurrence of disturbance are two major issues with DFIG based WPGSs.

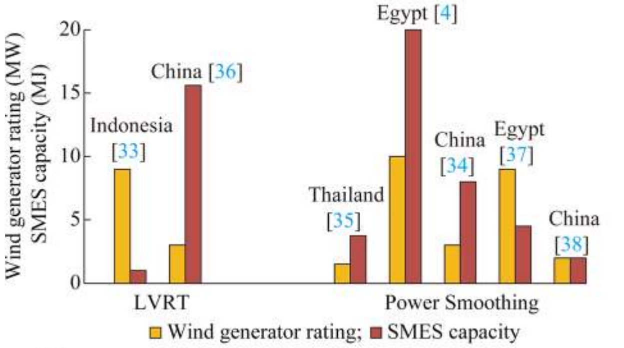
Power grids are synchronized by standards and grid codes, which aspire to ensure the stability and safety of the network by defining the guidelines of the technical and operational characteristics that have to be taken into account while interconnecting WPGSs to the grid. Grid codes are mainly concerned with voltage and frequency variations, fault events, reactive power capabilities, safety, and security of transmission systems. The required grid codes are typically defined at the point where the wind farms are connected to the grid (point of common coupling), but can sometimes also be defined at the point where a single wind turbine is connected to the grid (point of connection). In the wind industry, the most demanding requirements or grid codes are generally considered to be those followed in US, China and European countries such as Germany and UK [7–11].

These grid code requirements for both static and dynamic conditions of transmission system can be fulfilled either by developing control techniques or by incorporating flexible AC transmission system (FACTS) devices and energy storage systems (ESS) [12–17]. The first strategy is very complicated and needs robust controllers and cannot be implemented in existing WPGSs, while the second approach is more effective in order to ensure the reliability of power systems by supplying adequate reserve power against possible wind power fluctuations. Static synchronous compensator (STAT-COM), battery energy storage (BESS), Flywheel and superconducting magnetic energy storage (SMES) are generally used to overcome the discrepancies of wind integrated power systems.

High temperature SMES is an emerging ESS for grid applications. It consists of a high temperature superconducting (HTS) coil magnet, a cryogenic and vacuum system, a quench protection circuit, a converter, a control system, a transformer and a passive filter circuit. A SMES unit can store or discharge large amounts of electric energy in a very short period of time. In comparison to other ESSs, SMES has a high cyclic efficiency that exceeds 90%, large power density, quick response time and unlimited charging and discharging cycles [18, 19]. Recent developments of HTS SMES [20–31] in different countries are shown in Fig. 1a. Based on the converter, SMESs are of two types, VSC-SMES and current source converter (CSC)-SMES [32]. Though there are some operational and functional differences, both of these SMESs can supply the required active and reactive powers to overcome some of the major limitations of WPGS. Required SMES capacities for output power smoothing and LVRT requirement of WPGS are shown in Fig. 1b [4, 33–38]. In two different studies of power smoothing in China, the required SMES capacities are different. Reference [34] integrated 3 MW PMSG with grid. A 4 H SMES coil is connected at the conversion system of PMSG. The SMES requires 2 kA current to level the output power fluctuation of wind generator. The required stored energy of SMES in this study is 8 MJ. Whereas reference [38] connected 2 MJ SMES at the point of common coupling (PCC) in a 2 MW DFIG integrated grid for power smoothing. Therefore, the required stored energy of SMES is less in the latter study than that in the



(a) Worldwide developed SMES coil capacities



(b) SMES capacities required for LVRT and output power levelling

Fig. 1 Worldwide SMES coil capacities and requirements

former. The Global Industry Analysts Inc., USA recently announces that the global market for SMES systems is projected to reach US$ 64 million by 2020, driven by the escalating demand for advanced energy storage technologies in on-grid and off-grid applications [39].

Due to environmental necessity of WPGSs and the increasing demand of SMES systems, it is required to review the ongoing and recent research on applications of SMES in WPGS integrated to the power grid. While there are some reviews on ESS systems for wind and other renewable systems [40, 41], no attention has been given to different applications and connections of SMES system in WPGS integrated power grid. SMES is used in WPGS integrated system not only for power fluctuation and LVRT applications but also for load levelling, spinning reserve, voltage stability, etc. On the other hand, SMES units connected at different locations of wind integrated power system are different in capacities and have different impacts on the system. Therefore, optimization of SMES location is required for cost effective and efficient performance.

This paper firstly reviews the operational effect of different connections of SMES in WPGS integrated grid; secondly it discusses different applications of SMES to fulfill the grid code requirements of wind power integration; thirdly, optimization approaches are proposed for the locations of SMES to recover the instabilities of wind integrated power system to minimize the installation and operation cost of SMES; lastly, the total cost of WPGS and SMES combined system is studied and assessed. The key findings and challenges are discussed in the conclusion.

2 Connection of SMES in WPGS integrated grid

Figure 2a shows the locations of SMES for different wind generators. SMES can be connected either at the terminal of wind generator C1 [42], or at the conversion system C2 [34, 36, 38, 43–45], or at the PCC C3 [33, 46–53], or at the tie line C4 of a multi-bus power system connected with wind farm [54–56]. The connection topology of SMES for locations C3, C4 is shown in Fig. 2b and that for location C2 is shown in Fig. 2c. Four connection schemes are briefly explained below.

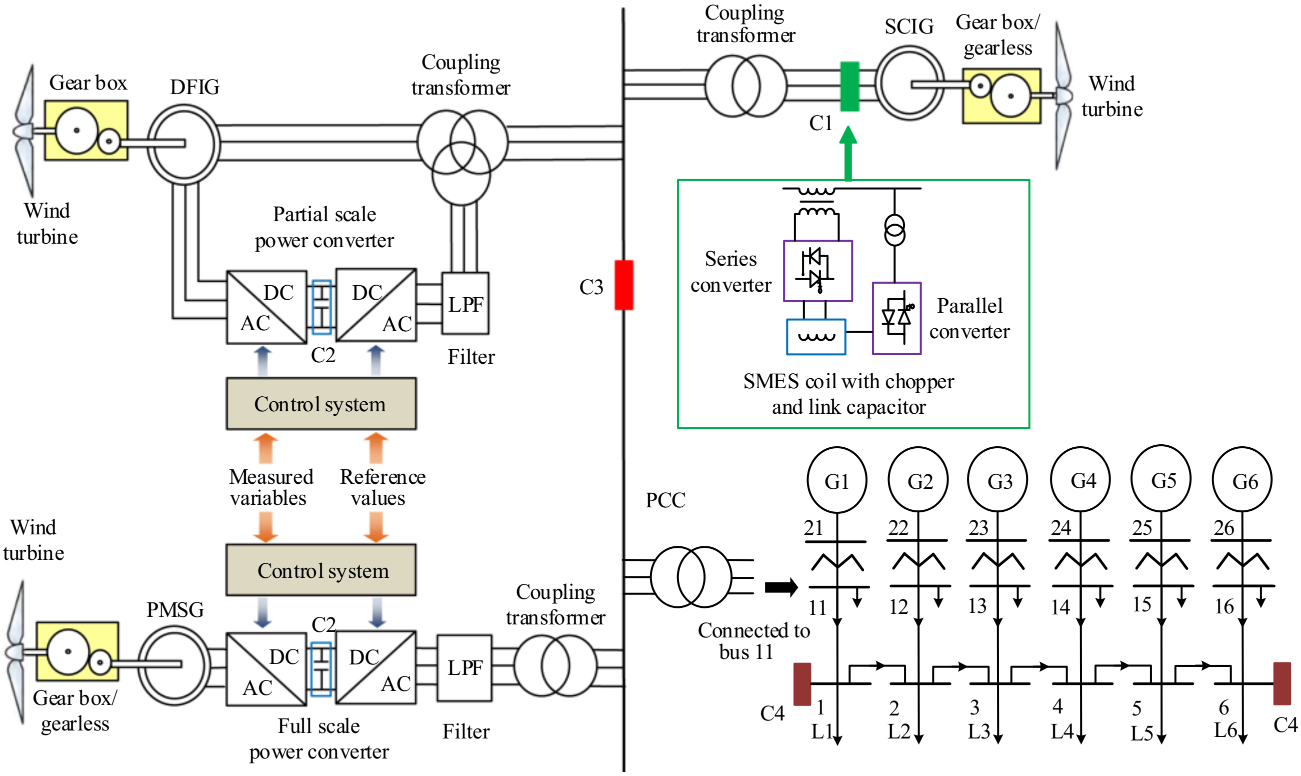
2.1 SMES at WPGS terminal (C1)

When SMES is connected at C1, one side of it is connected to the terminal of SCIG based FS-WPGS in series through converter and transformer, and the other side is connected in parallel through another converter. Series converter stabilizes the WTG terminal voltage and suppresses the fault current at the time of interconnection and during grid fault. On the other hand, parallel converter damps down the output power oscillations [42].

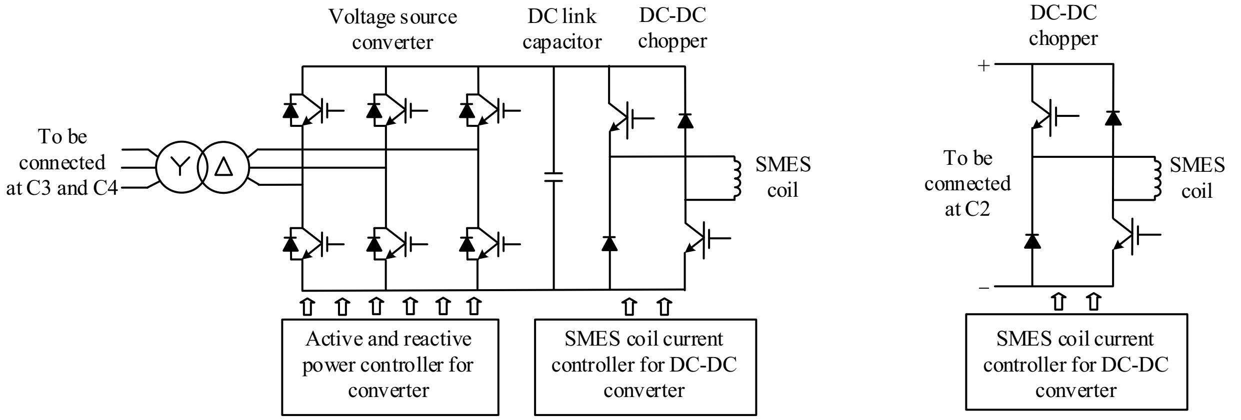
2.2 SMES at conversion system (C2)

This connection is only possible for VS-WPGSs, as these generators have conversion systems. SMES is connected at the conversion system (C2 in Fig. 2a) of PMSG and DFIG. Similar to SMES converter topology, VS-WPGSs are of two types: VSC based and CSC based. RSC and GSC are connected back to back through DC link capacitor in VSC based WPGS and through DC link choke in CSC based WPGS.

SMES is connected across the DC link capacitor of VS-WPGS through a two quadrant D type chopper as shown in Fig. 2c. Very high capacity SMES is required to mitigate the power fluctuations for C2, otherwise the result is not significant. In CSC based WPGS, the DC link capacitor can be replaced by a series connected SMES coil. In this case, the circuit complexity is less than that in the VSC based WPGS. Also, chopper circuit and its controller are not required, which makes the CSC based WPGS more cost effective [36]. SMES can compensate power fluctuation of wind generators while connected across DC link capacitor of partial conversion system of DFIG C2. While connected at C2, SMES is unable to improve the LVRT capability, as it cannot control the electromagnetic torque and suppress the stator current during grid fault. To overcome this, an



(a) Different locations of SMES in WPGS integrated power system



(b) SMES circuit diagram for locations C3 and C4 **(c)** SMES circuit diagram for location C2

Fig. 2 Different locations of SMES and circuit diagrams

additional diode rectifier circuit is used to connect SMES coil in series with the stator terminal where it can limit the fault current by introducing inductive impedance. However, it cannot compensate voltage dip at PCC to ensure the LVRT requirements [43].

2.3 SMES at PCC (C3)

The SMES connected at the PCC (C3 in Fig. 2a) of SCIG can mitigate the power oscillations. Conventional VSC based SMES as shown in Fig. 2b with PI controllers are generally used. SMES ratings are determined by the number of WPGS interconnections at PCC. Reference [33] used 1 MJ SMES at the PCC of 9 MW wind farm. Hysteresis current controller is used for VSC and fuzzy logic controller is used for DC chopper. This system is able to mitigate power fluctuation up to 40%.

2.4 SMES at load bus (C4)

Figure 2a shows a 6–area interconnected power system. In this figure, 1–6, 11–16 and 21–26 represent load buses, high voltage buses and generating buses of 6–area power system respectively. These areas are connected through tie lines. The wind farm of 500 MW is connected at bus 11 of area 1. Two high capacity (800 MJ) SMESs are connected at location C4 as shown in Fig. 2a. Due to the implementation of wind farm, power at tie-lines fluctuates. With an SMES of optimum capacity and proper control strategy, one can mitigate the power deviation produced by wind farm situated at a distance [57]. Alongside, these SMESs can also solve other power system problems with stability and quality. Table 1 describes the advantages and disadvantages of different locations of SMES in WPGS.

3 Applications of SMES in WPGS integrated grid

Power system stability, quality and security are the three important aspects for energy supply and are affected by any disturbance in the system. Earlier, wind turbines were disconnected from grid during such disturbance and to reconnect after a certain period of time. Nowadays, as wind energy shares significant percentage of total power generation, such practice would be fatal. As wind energy is contributing a large amount of electricity source in the total electricity generation, these sources have to contribute to the grid stability. SMES is found to have excellent properties to enhance the stability and quality of wind integrated power system.

3.1 Power fluctuation

Variable wind speed results in a fluctuating output power which may make the grid's power unstable if the ratio of renewable generation to total generation is considerable. SMES is useful for compensation of fluctuating power, since it is capable of controlling both the active and reactive powers simultaneously and quickly [4, 36–38, 43–45, 49–51]. It is seen in literature that all the four connections (C1–C4 of Fig. 2) can mitigate the power fluctuations of WPGS. SMES with VSC topology is usually connected at the PCC of wind farm [4, 37]. Proportional integral (PI) and fuzzy controllers are mostly used to control the converter and chopper circuits. Active power is absorbed from or delivered to the power system by SMES. Active power is controlled to level the output power, whereas reactive power is controlled to regulate the voltage

Table 1 Advantages and disadvantages of different locations of SMES in WPGS

SMES location (refer to Fig. 2)	Advantages	Disadvantages
C1	1) Control active and reactive power outputs of WPGS 2) Control LVRT capability 3) Directly limit the fault current by absorbing power as load and control the electromagnetic torque during grid fault	Power electronic converters both in series and parallel with apposite controllers increase the cost
C2	1) Converter circuit is not required for CSC 2) DC-DC chopper circuit is required for VSC 3) SMES connection is cost effective 4) Effectively reduce the output power fluctuation of WPGS 5) Exchange active power with rotor (DFIG) and reactive power with grid	1) Cannot enhance LVRT capability and has no control on stator current directly 2) An additional diode rectifier circuit is used to connect SMES coil in series with the stator terminal for LVRT [39] 3) High capacity of SMES is required for CSC based PMSG; however it is less for VSC based WPGS 4) Can be implemented in variable speed WPGSs only 5) Cannot be implemented in WPGS systems that are already installed
C3	1) Control active and reactive power outputs of WPGS 2) Can improve LVRT 3) Can handle problems at the grid side, load levelling, load frequency control, etc. 4) Can be implemented in all types of WPGSs (FS, VS)	1) All the equipment of SMES unit is required, increasing the cost of conversion and control; 2) If fault at grid side is nearer to PCC, then effect of SMES is less
C4	1) Reduce power fluctuations of the tie-line connected to WPGS 2) Can handle other problems (load levelling, voltage stability, frequency stability, etc.) of power system 3) Can be implemented in all types of WPGSs	1) Cannot improve the wind power penetration 2) Cannot be used as spinning reserve or for shift operation 3) Cannot improve the LVRT capability of WPGS

profile of PCC. The power drawn from stored energy of SMES coil should have a limit to avoid heating and to prevent loss of its superconductivity and coil burning. The overcharge and deep discharge process of SMES should be controlled in accordance with these limits [44]. Control strategies must be designed to maintain SMES current within normal range and to charge SMES in low current condition. At low current condition, wind generator supplies power to the SMES for charging and to the grid at the same time [34]. However, determination of SMES capacity and its location is very difficult as the SMES should handle not only the power fluctuation but also the different power flow situations.

Table 2 shows a performance comparison of SMES at WPGSs integrated power system, where α is defined as the ratio of the capacity of SMES and the rating of wind generator. C1–C4 are the locations of SMES when WPGS is connected with an AC power system as in Fig. 2a. On the other hand, when WPGS is connected to a high voltage direct current (HVDC) system, the generated output AC power of WPGS is first converted to DC and then linked with "DC bus". To reduce the output power fluctuations of WPGS, SMES is connected at the "DC bus". It can be seen in Table 2 that DFIG gives a better result with SMES in smoothing power fluctuation than the other two wind generators (PMSG and SCIG). Depending on the wind intermittency, output power of WPGS as well as SMES charging and discharging states varies. Table 2 shows that if SMES needs to change its states in small time intervals to smooth the output power of WPGSs, then the required α (MJ/MW) is low. On the other hand, if SMES needs to remain in one state for a long time then the required α (MJ/MW) is high.

3.2 LVRT

LVRT or fault ride through (FRT) is the requirement of minimum voltage limit that generating plants must have while operating through short periods of low grid voltage without disconnection. This voltage limit is defined in grid codes of different countries and highly depends on the system parameters. During grid faults like lightning strikes or short-circuits, transient voltage dips may occur. This appears as large loads connected to grid. After clearance of fault, the voltage must be raised to the pre-fault value within a specified period of time. SMES can maintain the grid voltage by injecting reactive power into the network [33–36, 45, 47–49, 57]. Like this, SMES improves the LVRT capability of WPGS. Compared to pitch control strategy, SMES gives better LVRT [48].

Hysteresis-current / fuzzy controllers are generally used for SMES connected at PCC (location C3 in Fig. 2) to

Table 2 Application of SMES for power fluctuation compensation – case studies

Wind generator type	Rating of wind generator (MW)	Capacity of SMES (MJ)	α (MJ/MW)	Controller	SMES location	Smoothing effect by SMES (%)	Remarks on required SMES capacity
PMSG [44]	1.500	450	300	–	C2	75	Long time (20 min) discharging
PMSG [36]	2.500	15.600	6.240	–	C2	88	–
PMSG [45]	3	2.577	0.895	–	C2	46	Alternate charging / discharging
DFIG [43]	0.500	2.250	4.500	–	C2	68	Longer charging time
DFIG [51]	0.075	0.100	1.333	–	C2	100	–
DFIG [47]	1.500	8.060	5.373	PI / PI	C3	85	Longer charging time
DFIG [49]	1.500	3.740	2.493	PI / PI	C3	100	Longer discharging time
DFIG [46]	2	2	1	PI	C3	100	Longer charging time
DFIG [35]	1.500	2.380	1.587	PI	DC Bus	100	Alternate charging / discharging with small intervals
DFIG [58]	1000	60000	60	–	DC Bus	100	–
SCIG [4]	10	20	2	PI / PI	C3	73	Long charging time
SCIG [42]	1.700	4.960	2.918	PI / PI	C1	83	Long charging time
SCIG [37]	9	4.500	0.500	PI / FLC	C3	57	Alternate charging / discharging with small intervals
Wind farm [50]	100	540	5.400	–	C2	80	–
Wind farm [54]	500	800	1.600	PI	C4	46	Alternate charging / discharging with small intervals
Wind farm [55]	500	800	1.600	Robust	C4	75	Alternate charging / discharging with small intervals

improve the FRT capability of WPGS [33]. It is seen that, when SMES is intruded inside the DFIG conversion system (location C1 in Fig. 2), it is unable to improve LVRT. This is because SMES can stabilize the DC-link voltage and smooth the output power simultaneously during normal condition, but the over current and electromagnetic torque oscillations cannot be eliminated during fault. The back electromotive force (EMF) induced in rotor generally becomes several times higher than the rated RSC voltage during fault and hence the RSC loses control over the rotor current. Therefore, the superconducting coil (SC), to work as superconducting fault current limiter (SFCL), is directly connected to the stator terminals of DFIG so as to limit the surge current when grid fault occurs [43]. Another method is taken to overcome this LVRT problem by implementing SFCL and SMES combined technology [47, 49] at PCC.

3.3 Power quality

Power quality is generally expressed in terms of voltage and frequency. Power system having good power quality means it has constant sinusoidal voltage with rated frequency and without high frequency noise (flicker or harmonics). In wind power generation, voltage variation is produced due to variations in energy content of the wind and interruptions during high wind speed. The SMES unit having VSC type converter can fulfil the reactive power of wind generators and improve the power quality by stabilizing voltage [51, 52, 58]. SMES improves voltage sag up to 97%; however, if the voltage sag lasts for a long time, SMES may completely get discharged and unable to improve voltage sag for the full fault duration [52].

3.4 WPGS stability

Misfire and fire-through are defined as the failure of the converter switch to TURN-ON and TURN-OFF at a scheduled conducting and non-conducting periods respectively. The effect of fire through and misfire of WEGS for fraction of seconds at a switch of either GSC or RSC produces oscillations in output power and voltage. Misfire has very little effect on DFIG output and shaft speed than fire through fault [46]. SMES compensates the deviation in DFIG output during misfire or fire through faults.

3.5 Load frequency control

A sudden load perturbation causes instant disparity between load and generation. When the loads are increased above the rated power output of the generators during low wind speed, a power imbalance will take place causing a load frequency control problem [33]. This issue is more severe in case of DFIG-based WPGS due to low inertia with respect to their power rating.

Due to load change, power transfer to grid also deviates from the rated power. This creates power imbalance between load and wind power output. SMES, connected at PCC of DFIG based WPGS, can improve the load profile by discharging and charging during overload and under load conditions respectively [33].

3.6 Spinning reserve

Power system always needs reserve power to overcome the possible power outage of generation unit. In order to maintain the reliability of power systems, reserve power needs to be scheduled against possible generation unit outages. Like conventional generators, WPGSs do not have the spinning reserve so as to support power system reliability. On the other hand, SMES can reserve GW of power to achieve the reserve requirements of WPGS [56]. During high wind speed, it can store the excess energy and deliver this energy during isolation of WPGS.

4 Optimum location of SMES in WPGS integrated grid

There are some research studies on optimum placement of both wind generators and ESS [59, 60]. However wind generators may not be located optimally as it highly depends on the maximum undisturbed wind flow and low cost area. For these reasons, wind power cannot be distributed in the power system network. Therefore, there is a probability of having high power congestion due to power transmission limitations. The wind power curtailment occurs frequently in those areas with high wind power penetration. Probable ways to alter the power flow to avoid unexpected congestion of power include change in system topology, use of flexible AC transmission systems, redispatch of generation, renewable energy source (RES) curtailment and use of ESS.

Redispatch is a message sent by the transmission utility to power plants to amend the real power generation in order to avoid power congestion. By storing the extra real power output of wind farms to ESS, it is feasible to alleviate congestion while real power in the grid is maintained at rated value. On the other hand, the wind power curtailment, due to limited transmission capacity, can be mitigated by ESS. ESS can balance the generation- demand mismatch by storing and delivering power during peak and down load conditions respectively.

Sufficient studies have been done on optimum location and size of ESS in renewable integrated power system. These studies are focused on minimizing the annual investment cost, operation and maintenance, installation cost, power loss cost, interruption cost and maximizing the utility, reliability, safety, stability, consumption of renewable energy. Most of these studies use optimal power flow (OPF), genetic algorithm (GA), particle swarm optimisation (PSO) and block coordinate decent (BCD) algorithms programmes [61–71]. The constraints considered in these studies are based on conventional power system constraints, cost constraints, ESS constraints and renewable energy constraints. The conventional power system depends on generator ramp limit, power transfer capacity, power balance, bus voltage limit, reverse power flow from substation transformer and spinning reserve. The ESS constraints depend on storage capacity, charging/discharging energy and power, state of charge. The constraints for renewable energy generation include abandoned energy, power output and curtailment.

Some research works are focused on the optimization of location and capacity of BESS [72–77]. In these studies maximum storage capacity, charging/discharging power, state of charge, lifespan, cost and total benefit of BESS are considered. These methods can be followed in case of optimum location of SMES by considering its constraints in the optimization programming. Table 3 shows the constraints of SMES to be considered in the optimization algorithm. Local optimization can find the location and capacity of SMES for any one of the problems of wind integrated power system, such as power quality, FRT capability, power oscillation etc. Therefore, to get the globally optimized location, multi-objective and multi-area optimization is required to realize the total benefit of SMES.

In Table 3, $E_{\mathrm{SMES},t}$, $E_{\mathrm{SMES,min}}$, $E_{\mathrm{SMES,max}}$ are the instantaneous, minimum and maximum stored energy in SMES respectively; $P_{\mathrm{ch},t}$, $P_{\mathrm{dis},t}$ are the instantaneous charging and discharging power of SMES respectively; $P_{\mathrm{SMES,min}}$, $P_{\mathrm{SMES,max}}$ are the minimum and maximum power of SMES; $E_{\mathrm{SMES},t\text{-}1}$ is the stored energy in SMES at the previous instance; η_{ch}, η_{dis} are the charging and discharging efficiencies of SMES; $T_{\mathrm{SMES},t}$ is the instantaneous value of temperature of SMES; T_{c} is the critical temperature of SMES; $V_{\mathrm{SMES},t}$, $I_{\mathrm{SMES},t}$ are the voltage and current in SMES; $V_{\mathrm{lim},t}$, $t_{\mathrm{lim},t}$ are limitations in voltage values and transition time of SMES; $I_{e,t}$, L are the instantaneous current and self-inductance in e^{th} coil segment of SMES; I_{c} is the critical current of SMES; $E_{\mathrm{J},t}$, R_{en} are Joule heating, and resistance appearing in the coil segment during quench; $P_{\mathrm{SMES}}^{\mathrm{rated}}$, $E_{\mathrm{SMES}}^{\mathrm{rated}}$ are rated power and energy of SMES; C_0 is a constant cost to retain superconductivity; $P_{\mathrm{wind},i}$, $P_{\mathrm{gen},j}$, $P_{\mathrm{load},k}$ are active power of wind generator, conventional generator and load connected at i^{th}, j^{th} and k^{th} bus respectively; l, m, n are number of buses of wind generator, conventional generator and load respectively.

Table 3 SMES constraints for optimal location and sizing

Parameters of SMES	Constraints
Storage capacity	$E_{\mathrm{SMES,min}} \le E_{\mathrm{SMES},t} \le E_{\mathrm{SMES,max}}$
Charging / discharging	$P_{\mathrm{ch},t} \ge P_{\mathrm{SMES,min}},\ P_{\mathrm{dis},t} \le P_{\mathrm{SMES,max}}$
State of charge (SOC)	$\lambda_{\mathrm{SOC},t} = E_{\mathrm{SMES},t} / E_{\mathrm{SMES,\,max}}$
Energy transition	$E_{\mathrm{SMES},t} = E_{\mathrm{SMES},t-1} + \left(P_{\mathrm{ch},t}\eta_{\mathrm{ch}} - P_{\mathrm{dis},t}\eta_{\mathrm{dis}}\right)\Delta t$
Life span factors	Life span can be considered infinity with respect to BESS
Temperature	$T_{\mathrm{SMES},t} < T_{\mathrm{c}}$
Voltage across SMES	$V_{\mathrm{SMES},t}\left(= L\Delta I_{\mathrm{SMES},t}/\Delta t\right) \le V_{\mathrm{lim},t}$
Transition time	$\Delta t \ge t_{\mathrm{lim},t}$
Charging / discharging current constraints for quench	$\begin{cases} I_{e,t}L\dfrac{\mathrm{d}I_{e,t}}{\mathrm{d}t} < E_{\mathrm{J},t} & I_{e,t} < I_{\mathrm{c}} \\ I_{e,t}L\dfrac{\mathrm{d}I_{e,t}}{\mathrm{d}t} + I_{e,t}^2 R_{en} \ge E_{\mathrm{J},t} & I_{e,t} \ge I_{\mathrm{c}} \end{cases}$
Investment, operation and maintenance cost	Linear with SMES rating ($P_{\mathrm{SMES}}^{\mathrm{rated}}$ and $E_{\mathrm{SMES}}^{\mathrm{rated}}$)
Lifespan cost	Can be neglected as replacement is not required for long time
Pollution emission cost	As a magnetic device, it has no pollution emission cost
Converter cost	Linearly varies with $P_{\mathrm{SMES}}^{\mathrm{rated}}$
Cryogenic cost	Linearly varies with $P_{\mathrm{SMES}}^{\mathrm{rated}} + C_0$
Operation of SMES	$\begin{cases} P_{\mathrm{SMES}} < 0 & \sum\limits_{i=1}^{l} P_{\mathrm{wind},i} + \sum\limits_{j=1}^{m} P_{\mathrm{gen},j} > \sum\limits_{k=1}^{n} P_{\mathrm{load},k} \\ P_{\mathrm{SMES}} > 0 & \sum\limits_{i=1}^{l} P_{\mathrm{wind},i} + \sum\limits_{j=1}^{m} P_{\mathrm{gen},j} < \sum\limits_{k=1}^{n} P_{\mathrm{load},k} \end{cases}$

Table 4 Capital cost of WPGS and SMES

Device	Parts	Cost (%)	Overall cost (WPGS + SMES) (%)
WPGS [79]	Structural cost	52	50.5
	Rotor blade and pitch controller	23	22.3
	Gearbox	11	10.7
	Power converter	6	5.8
	Transformer	5	4.9
	Generator	3	2.9
SMES [81]	SMES Coil	30	0.9
	Power converter	60	1.7
	Cryogenics	10	0.3

5 Cost effects

Onshore wind WPGS cost is about 50% that of the offshore WPGS [78]. The total cost of onshore wind turbine depends on wind turbine, grid connection and installation. The cost of wind turbine depends on turbine blades, gearbox, power converter, controller, transformer, civil construction and others. Gearbox cost can be reduced by using VS wind turbine because of its high power extracting efficiency within the range of sub-synchronous and super-synchronous speeds [79]. The cost of power converter is 6% of total wind turbine cost. This can be reduced to 2.5% for DFIG type wind turbine as the required converter capacity is 30% of the rated power of the wind generator [80].

When SMES is connected to the WPGS, the cost of its pitch control, gearbox, power converter system and control system are affected. However, due to high cost of HTS tape, the addition of SMES to WPGS increases its capital cost to 3% (explained in Table 4). The cost as well as the capacity of SMES connected to the wind turbine differs with the location of connection and type (VSC or CSC) of SMES [82–85].

6 Conclusion

In this paper, an effort is given to explain SMES device and its controllability to mitigate the stability of power grid integrated with WPGS. There are four possible locations of SMES in WPGS integrated power system: at wind generator terminal, at conversion system, at PCC and at tie-line. For any of these locations, SMES can suppress the power fluctuations. However, to improve the LVRT the location of SMES is preferred at PCC or terminal of the WPGS.

The key findings of this work are:

1) SMES at PCC can mitigate both WPGS and grid issues.
2) SMES cannot enhance the LVRT capability for the locations at conversion system and tie-line.
3) A huge variation of SMES capacity is noticed in different research papers of similar applications. 0.45 GJ and 2.577 MJ SMES are connected at the conversion system of 1.5 MW [44] and 3 MW [45] PMSG based WPGS respectively. The reason is that the wind speed pattern of the previous study [44] requires long time (20 min) discharging of SMES, whereas that of the latter study [45] requires alternative charging / discharging for small intervals.

The challenges to be taken to commercialize SMES in wind integrated grid are:

1) Improvement in long length HTS tapes with reduced cost for adequate use of HTS SMES in wind generator integrated power system.
2) Optimization of SMES capacity, location and control for efficient and cost effective wind power penetration.

However, the SMES unit is still a costly piece of equipment. Its commercialization requires improvements in superconducting splice technology to develop uniform superconductors of long length with capacity to bear up high magnetic fields.

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