Frequency Regulation Support by Variable-Speed Wind Turbines and SMES

M. Saleh, and H. Bevrani

Abstract—This paper quantifies the impact of providing a short-term excess active power support of a variable speed wind turbine (VSWT) and effect of super magnetic energy storage (SMES) unit on frequency control, particularly temporary minimum frequency (TMF) term. To demonstrate the effect of these factors on the power system frequency, a three-area power system is considered as a test system.

Keywords— Frequency regulation, inertia, primary frequency control, rotational energy, variable speed wind turbine.

I. INTRODUCTION

The number of wind turbines connected to the grid is increasingly developed whereas concern about frequency variation of power system in experienced due to wind generation output fluctuation. With increase wind farms installation, frequency control of power system by main conventional sources, that is hydraulic and thermal power stations, will be difficult in the near future hence, some strategies are necessary to improve the stability of wind power output.

In general, wind turbine generators (WTGs) can be divided into two principle categories: fixed speed and variable speed. Fixed speed WTG is not provide ancillary services as a general rule but provides an inertial response due to the stored a considerable amount of energy when the system frequency falls. Doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) are common types of variable speed WTG. Variable speed WTG offer improved ancillary service capabilities over fixed speed WTG whereas do not provides any inherent response because of decoupling the rotor from the power system. The variable speed wind turbines (VSWTs) have the capability of active and reactive power control. The active power control is provided by resorting to the mechanical system kinetic energy. Wind farms do not participate in frequency control at present but in future will be required increasingly to offer performance similar to that provided by conventional large synchronous generators, and at least some of ancillary services that are necessary for the secure and stable operation of power system. The primary frequency regulation is based on a set of local controllers, each one responding to frequency deviations by adding or subtracting active power in proportion to the rated power of the respective unit, assuring in this way a new equilibrium point for the system.

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There are several proposals for implementing the primary frequency regulation in wind turbines. In [1], the control strategy adopted consists of an emulation of the proportional control implemented in conventional synchronous generators. Wind machines are forced to work keeping a regulation band for frequency control, thus not using their full capacity, by suitably combining both static converter and pitch control. In [2], the factors affecting the inertial response of a variable-speed wind turbine are studied. It is shown that the inertia effect of a doubly fed induction generator (DFIG)-based wind turbine is not completely hidden; rather it depends on parameters of the rotor current controller as slower current controller facilitates the inertial response. The work presented in [3] demonstrates the possibility of releasing kinetic energy from a DFIG-based wind turbine system by using an additional control loop, sensitive to the network frequency. The release in kinetic energy in this way is larger compared to that release from a fixed wind turbine system. In [4], some techniques to emulate additional inertia are presented. A quite similar concept (an additional network frequency depend control signal) to facilitate an inertia response from a DFIG-based system is presented in [5] and [6]. Therefore, introducing wind power into the power system will not necessarily reduce the inertia of the system if the control of a modern VSWT is modified, as presented in recent reports [2-7].

In a short-term view, ranging from fraction of a second to few seconds, the obtained mechanical power/torque from the wind is approximately constant and frequency support can be provided by the kinetic energy stored in the rotating masses. Due to the limited value of the stored kinetic energy, the contribution of wind units is limited to short periods of time. An improved performance may achieved by letting nearby conventional generators be aware of the contribution of wind units to frequency support [7].

In a midterm timescale, ranging from few seconds to minutes, mechanical power from the wind units is perturbed by wind speed changes and other factors, which can affect the overall frequency regulation. In order to reduce this impact, it is possible to modify the pitch angles or the output power, as proposed in [8], and also to consider the aggregated smoothing effect of a large number of the wind farms, as done in [9] and [10]. In long-term frameworks, from few minutes to hours, the total energy generated by wind units depends on the wind variation pattern. In this context, the control actions must be taken in order to increase the power

reserve of power systems, as studied in [11].

In [12], it is shown that the wind turbine under consideration can provide an extra 0.1 pu of active power for more than 10 seconds quite easily without hitting the minimum speed limit of the turbine for all wind speeds. This result is used in the present paper.

Most of the works concerned with frequency control problem of interconnected power systems have shown that, to compensate of sudden load changes, an active power source with fast response such as superconducting magnetic energy storage (SMES) unit is expected to be the most effective counter- measure. The reported works [13-17] further shows that, SMES is located in each area of the power system for frequency control problem. With the use of SMES in all areas, frequency deviations in each area are effectively suppressed. However, it may not be economically feasible to use SMES in all areas of a multi-area interconnected power system. Therefore, it is advantageous if an SMES located in an area is available for the control of frequency of other interconnected areas.

II. SMES MODEL

The schematic diagram in Fig. 1 shows the configuration of a thyristor controlled SMES unit. In the SMES unit, a DC magnetic coil is connected to the AC grid through a power conversion system (PCS) which includes an inverter/rectifier. The current in the superconducting coil will be tens of thousands or hundreds of thousands of amperes.

No AC power system normally operates at these current levels and hence a transformer is mounted on each side of the converter unit to convert the high voltage and low current of the AC system to the low voltage and high current required by the coil. The energy exchange between the superconducting coil and the electric power system is controlled by a line commutated converter. To reduce the harmonics produced on the AC bus and in the output voltage to the coil, a 12-pulse converter is preferred [18].

When, the superconducting coil is charged, the current is conducted with virtually no losses [13-18] as the superconducting coil is kept at extremely low-temperatures. As explained in [18], neglecting the transformer and the converter losses, the DC voltage is given by:

$$E_d = 2V_{d0}\cos\alpha - 2I_d R_c \tag{1}$$

where, the E_d is the DC voltage applied to the inductor in kV, and α is the firing angle (in degrees) produced by switching driver circuit. When α is less than 90°, converter acts in the converter mode (charging mode) and when α is greater than 90°, the converter acts in the inverter mode (discharging mode). The I_d is the current flowing through the inductor in kA, R_c is the equivalent commutating resistance in kΩ, and V_{d0} is the maximum circuit bridge voltage in kV.

In load-frequency control (LFC) operation, the Ed should be continuously controlled by the input signal to the SMES control logic. As mentioned in recent literatures [13-18], the inductor current must be restored to its nominal value quickly after a system disturbance so that it can immediately respond to the next load disturbances. Thus, in order to improve the current restoration to its steady state value the inductor current deviation is used as a negative feedback signal in the SMES feedback control loop. Based on the above dissuasion, the converter voltage applied to the inductor and inductor current deviations are described as follows:

$$\Delta E_{di}(s) = \frac{K_{SMES}}{1+sT_{dci}} u_{SMESi}(s) - \frac{K_{id}}{1+sT_{dci}} \Delta I_{di}(s) \tag{2}$$

$$\Delta I_{di}(s) = \frac{1}{sL_i} \Delta E_{di}(s) \tag{3}$$

In this study, as in recent literatures, the input signal to the SMES control logic is considered the ACE_i of the same area in power system. The ACE_i is defined as follows:

$$ACE_i = B_i \Delta F_i + \Delta P_{tie,i} \tag{4}$$

The deviation in the inductor real power of SMES unit is expressed in time domain as follows:

$$\Delta P_{SMESi} = \Delta E_{di} I_{d0i} + \Delta I_{d0i} \Delta E_{di} \tag{5}$$

This value is assumed positive for transfer from AC grid to DC. Fig. 2 shows a simplified block diagram for a SMES unit.
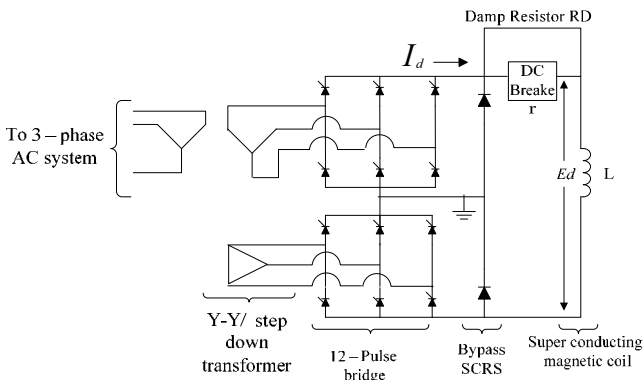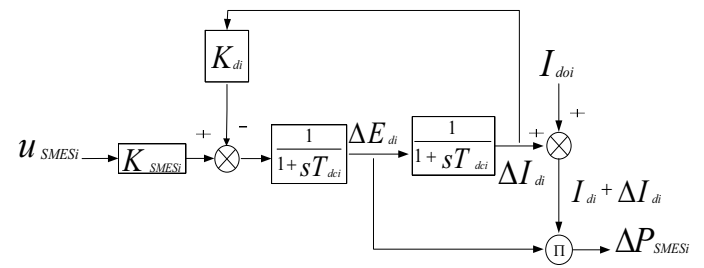

Fig.1 SMES circuit diagram

Fig. 2 The block diagram of SMES unit

III. FREQUENCY CONTROL THROUGH VSWTs

It is investigated that during operations, a wind unit has rotational energy stored in the turbine and generator, which is quite comparable with that of conventional generators [5]. This energy can be used to provide temporary primary frequency control support to the grid in the event of a load/generator mismatch. The fixed speed wind turbines are directly coupled to the grid frequency and their rotational speed cannot be varied freely. The VSWTs, on the other hand, have power electronic interfaces and the rotational speed is decoupled from the grid frequency. The VSWTs are designed to be able to vary their rotational speed in a wider range during normal operations which gives the possibility to utilize the rotational energy in the turbine-governor to provide short-term active support in the event of network frequency excursions. The VSWTs with full power converters have the possibility to operate in a wider range of speed than DFIG-based wind turbines with partial scale frequency converters, and also allow using the rotating energy in the turbine-governor further [12].

To facilitate the excess active power injection from the wind turbine, upon the detection of a network frequency disturbance (when the frequency is outside a predefined dead band), the normal control of the turbine can be bypassed and a predefined power demand on top of the pre disturbance value can be made to the converter controller to take out some rotational energy from the rotor blades for a certain predefined time. The excess power could, for instance, be the value that will be required to maintain the temporary minimum frequency of the system within an acceptable level [12].

After this predefined time period, a rapid decrease in the power demand can also be made from the pre disturbance value for a certain predefined time which will result in an accelerating operation of the turbine blade. This accelerating time can be chosen based on the energy equilibrium. And after this accelerating time, the control can be switched to the normal wind turbine control. To reduce the pressure on the rest of the system, the accelerating period of the turbine can be longer than the decelerating period as shown in Fig. 3 [12].
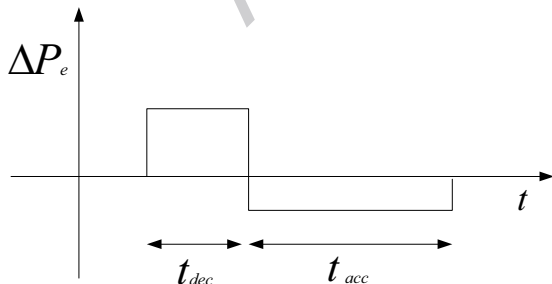

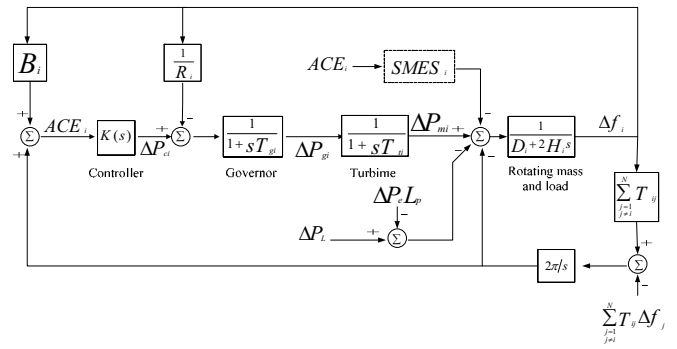Fig. 3 Temporary extra active power support by VSWT

Fig.4 Block diagram of a LFC model

IV. DESCRIPTION OF LFC SHEME

In the LFC analysis, all the generators of a system is represented by an equivalent generator, which has an equivalent inertia constant and is driven by the combined mechanical output of the individual turbine [19]. The complete diagram of LFC system is shown in Fig. 4. To augmentation of system with the incoming wind generation, in consistent with [12], the following assumptions are considered: *i*) the wind turbines to be installed do not respond to network frequency deviations, and the total load of the system remains the same; *ii*) an x% wind penetration means an x% reduction in the existing generating units, i.e., an x% reduction in the system inertia. Furthermore, the droop settings of the individual generators remain the same; and *iii*) the spinning reserve in the power system is enough to take up any generation deficit.

The way to consider the excess active power injection from the wind turbine into the power system is presented in Fig. 4. ΔP_e is multiplied with the penetration level L_p to convert ΔP_e from the wind farm (WF) base to the system MVA base. The effective load step in the presence of the WF is [12]:

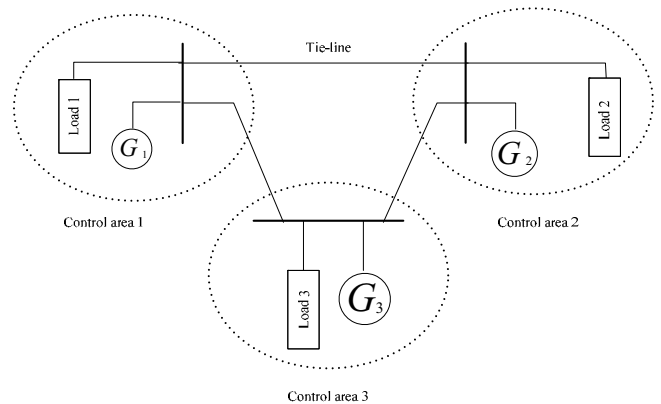$$\Delta P_{L,new} = \Delta P_L - \Delta P_e L_p \qquad (6)$$

Fig.5 Three-control area power system

V. SIMULATIONS

To illustrate the LFC system behavior in a multi-area power system, consider three identical interconnected control areas as shown in Fig. 5, which is taken from [20].

The simulation parameters are given in Appendix. Several simulations following a simultaneous 0.02-pu load step disturbance in control areas 1 and 3 have been performed. In control area 3, in one state assumed wind penetration is equal 20% and the SMES and VSWT frequency support with different states is considered. For the VSWT frequency support a 0.05 pu (on the WF WVA base) is considered where decelerating time is equal to 10 s and accelerating time equal to 20 s assumed. The SMES parameters are given in the Appendix.

Fig. 6 and Fig. 7 show the frequency response of three areas. As a consequence of the increasing penetration level in area 3, the magnitude of the temporary minimum frequency of the three control area will increase as well as the frequency oscillation as shown in Fig. 6-a, Fig. 6-c, and Fig. 7-a.

As can be observed with the support from the WF, the temporary minimum frequency is improved compared to the case when no such support provided by the WF where the frequency oscillation after contingency operation (for 30 s). When the control of the WF is taken over by regular controller at 31 s, the frequency oscillation for areas 1 and 2 is higher than case that support from WF is zero.

Following adding the support of the SMES the frequency response is better. The temporary minimum frequency is improved and the frequency oscillation related to WF support is decreased. Notice that temporary minimum frequency improvement is further related to the support from the WF. This result can be found with compare the frequency support from SMES and WF.

VI. CONCLUSION

In this paper, the effect of temporary extra active power support from variable speed wind turbines (VSWT) as well as super magnetic energy storage (SMES) unit on the power system frequency response is investigated.

It is found that the VSWTs with frequency support can be decrease the temporary minimum frequency but cause to further frequency oscillation. With apply frequency support from VSWTs and SMES together, frequency response is improved.

Some simulations are performed on a three control areas power system, and the systems frequency response is examined for different scenarios with and without VSWT and SMES supports.
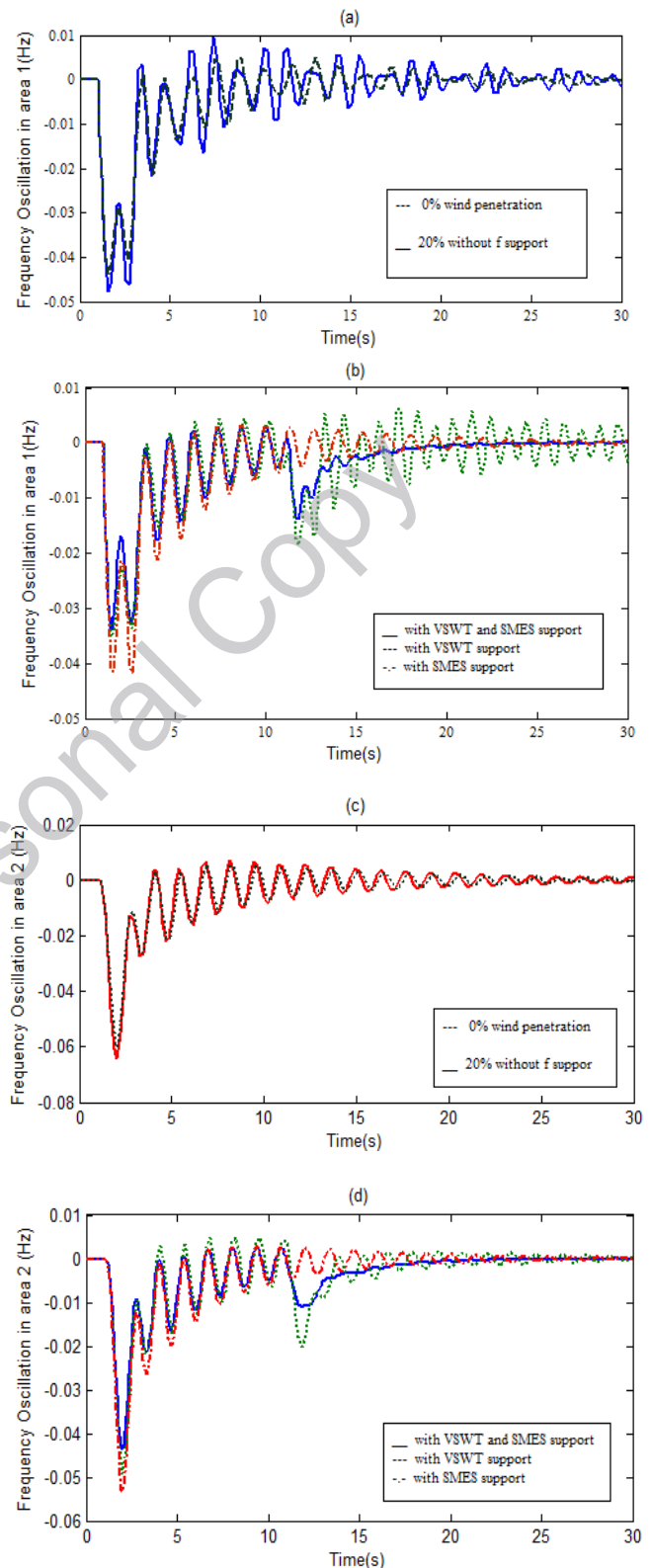

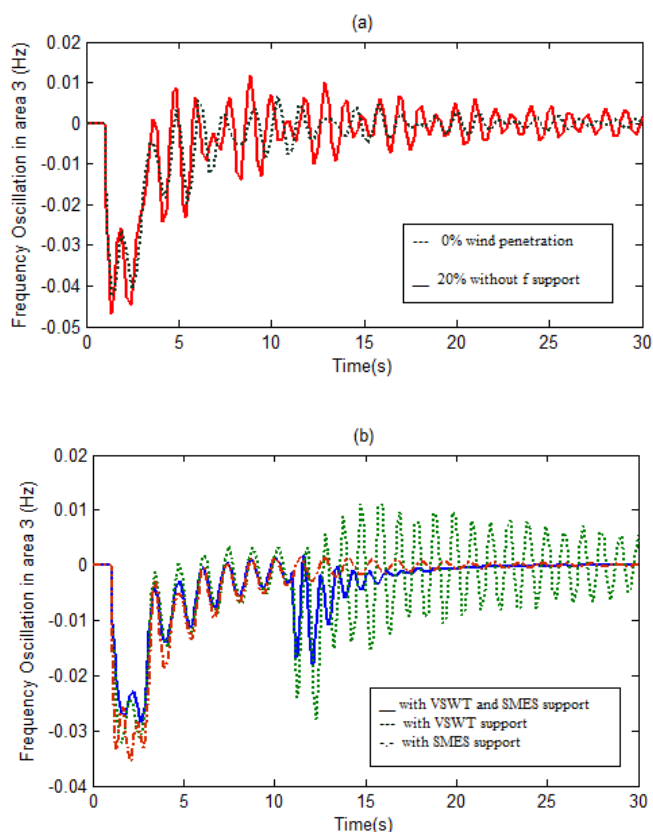Fig.6 Frequency response in areas 1and 2

Fig.7 Frequency response in area 3

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APPENDIX

A. SMES Data

$$L = 2.65 \text{ H}, \quad T_{dc} = 0.03 \text{ s},$$

$$K_{id} = 0.2 \text{ KV/KA}, \quad I_{d0} = 4.5 \text{ KA},$$

$$K_{SMES} = 100 \, \frac{KV}{unit} \text{MW}$$

B. 3-Control Area Simulation Parameters

TABLE I
SIMULATION PARAMETERS FOR FIG. 5

Area	Area 1	Area 2	Area 3
$K(s)$	-0.3/s	-0.2/s	-0.4/s
$D(pu/Hz)$	0.015	0.016	0.015
$2H(pu \, s)$	0.1667	0.2017	0.1247
$R(Hz/pu)$	3.00	2.73	2.82
$T_g(s)$	0.08	0.06	0.07
$T_t(s)$	0.40	0.44	0.30
$\beta(pu/Hz$	0.3483	0.3827	0.3692
$T_{ij}(pu/Hz)$	$T_{12} = 0.20$ $T_{13} = 0.25$	$T_{21} = 0.20$ $T_{23} = 0.12$	$T_{31} = 0.25$ $T_{32} = 0.12$