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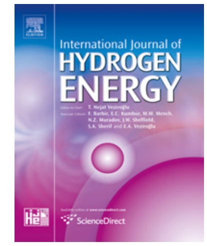

Stabilization and control of tie-line power flow of microgrid including wind generation by distributed energy storage

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ABSTRACT

High penetration of wind generation in electrical microgrids causes fluctuations of tie-line power flow and significantly affects the power system operation. This can lead to severe problems, such as system frequency oscillations, and/or violations of power lines capability. With proper control, a distribution static synchronous compensator (DSTATCOM) integrated with superconducting magnetic energy storage (SMES) is able to significantly enhance the dynamic security of the power system. This paper proposes the use of a SMES system in combination with a DSTATCOM as effective distributed energy storage (DES) for stabilization and control of the tie-line power flow of microgrids incorporating wind generation. A new detailed model of the integrated DSTATCOM-SMES device is derived and a novel three-level control scheme is designed. The dynamic performance of the proposed control schemes is fully validated using MATLAB/Simulink.

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1. Introduction

Distributed energy resources (DERs), including distributed generation (DG) and distributed energy storage (DES), are small sources of energy located near the demand site. This technological solution consolidates the idea of using clean technologies of generation that use renewable energy sources (RESs) [1,2].

At present, the most promising novel network structure that would allow obtaining a better use of DERs is the electrical microgrid (MG). This new concept tackles all DERs as a unique subsystem, including DG, RES, DES and demand response (DR), and offers significant control capacities on its operation. This electrical grid can be managed as if were a group with predictable generation and demand, and can be operated as much interconnected to the main power system as autonomously isolated [3].

Nowadays, grid integration of wind power generation is becoming the most important and fastest growing form of electricity generation among renewable energies. However, wind power frequently changes and is hardly predictable. The high penetration of wind generation with abrupt changes adversely affects the power system (PS) operation and can lead to severe problems. In order to overcome these problems, energy storage advanced solutions in combination with a recent type of power electronic equipments, such as distribution static synchronous compensator (DSTATCOM), can be utilized as an effective DES device with the ability to quickly

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exchange power with the microgrid and thus to balance any instantaneous mismatch in active power [4].

Various types of advanced energy storage technologies can be incorporated into the DC bus of the DSTATCOM, namely superconducting magnetic energy storage (SMES), super capacitors (SC), flywheels and batteries, among others. However, SMES devices stand out for their exceptional dynamic performance, including a rapid response (ms), high power (hundred MW), high efficiency, and four-quadrant control.

This paper proposes the use of a DSTATCOM-SMES as effective DES for stabilization and control of the tie-line power flow of MGs incorporating wind generation. A full detailed model of the integrated DSTATCOM-SMES is derived, including the superconducting coil (SC) and the power conditioning system (PCS) used to connect to power grid, as depicted in Fig. 1. The PCS consists of the DSTATCOM (AC/DC converter, transformer and filter) and incorporates a two-quadrant DC/DC converter as interface with the SMES coil. Moreover, a three-level control scheme is designed, comprising an enhanced power system frequency controller. The dynamic performance of the proposed systems is validated through digital simulation carried out with SimPowerSystems (SPS) of MATLAB/Simulink.

2. Modeling of the DSTATCOM-SMES

Fig. 2 summarizes the proposed detailed model of the DSTATCOM-SMES for dynamic performance studies in distribution power systems. This model consists mainly of the DSTATCOM, the SC coil and the DC/DC converter to interface both devices.

The DSTATCOM basically consists of a three-phase voltage source inverter (VSI) shunt-connected to the distribution network by means of a coupling step-up transformer and the corresponding line sinusoidal filter. The VSI corresponds to a DC/AC converter controlled through sinusoidal pulse width modulation (SPWM) techniques. The inverter structure is based on a diode-clamped three-level topology, also called neutral point clamped (NPC), instead of a standard two-level six-pulse inverter structure. This three-level twelve-pulse VSI topology generates a more smoothly sinusoidal output voltage waveform than conventional structures without increasing the switching frequency and effectively doubles the power rating of the VSI for a given semiconductor device. However, this topology has the drawback of not having balanced voltages among VSI DC capacitors when active power is exchanged. Thus, the use of a two-quadrant three-level DC/DC converter or chopper is proposed as interface between the DSTATCOM and the SMES, instead of a standard two-level one. This converter allows regulating the power exchange between the SMES coil and the DSTATCOM through a buck-boost topology control mode [5]. Moreover, the chopper makes use of the extra level to solve any problem of voltage imbalance. This is achieved by employing the various redundant switching states for generating the same output voltage vector but with different charge balance of the DC bus capacitors.

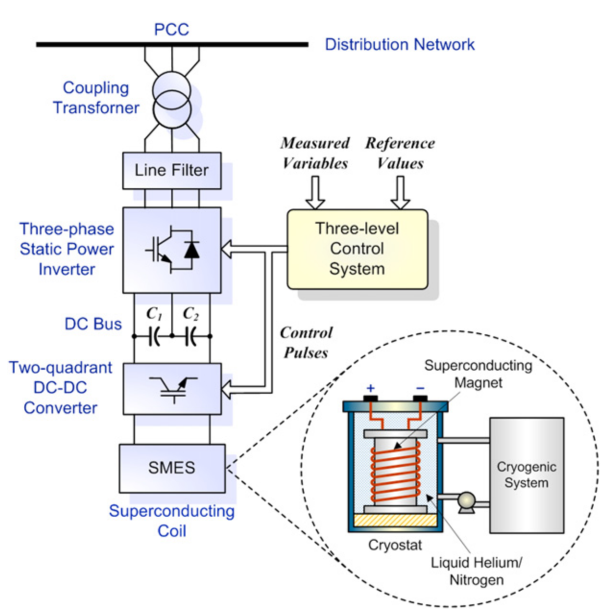

Fig. 1 – General structure of the DSTATCOM-SMES.

The equivalent circuit of the SMES coil makes use of a lumped parameter network implemented by a six-segment model based on [6]. This representation allows characterizing the voltage distribution and frequency response of the SC coil with reasonable accuracy over a frequency range from DC to several thousand Hertz. The model comprises self inductances (L_i), mutual couplings between segments (i and j, M_{ij}), AC loss resistances (R_{Si}), skin effect-related resistances (R_{Shi}), turn-ground (shunt–C_{Shi}) and turn–turn capacitances (series–C_{Si}).

3. Proposed control strategy of the DSTATCOM-SMES

The proposed hierarchical control of the integrated DSTATCOM-SMES consists of an external, middle and internal level, as depicted in Fig. 3.

3.1. *External level control*

The external level control, which is outlined in Fig. 3 (left side), is responsible for determining the active power exchange between the DSTATCOM-SMES and the microgrid. This control mode aims at controlling the microgrid frequency through the modulation of the active component i_d. To this aim, the reference i_{dr1} is forced to vary with a stabilizer signal proportional to the frequency deviation Δf (defined as $f_r - f$) which directly represents the power oscillation (or power swing) of the PS; the purpose of this variation being to effectively improve the damping of power system oscillations. Since a robust and efficient frequency control scheme requires the effective damping of a wide range of generators power oscillations, ranging from less than 0.2 Hz for global oscillations to 4 Hz for local oscillations of units, a flexible multi-band structure (MBS) controller is proposed in this work. In this way, the novel proposed compensator architecture depicted in Fig. 3 presents several degrees of freedom for

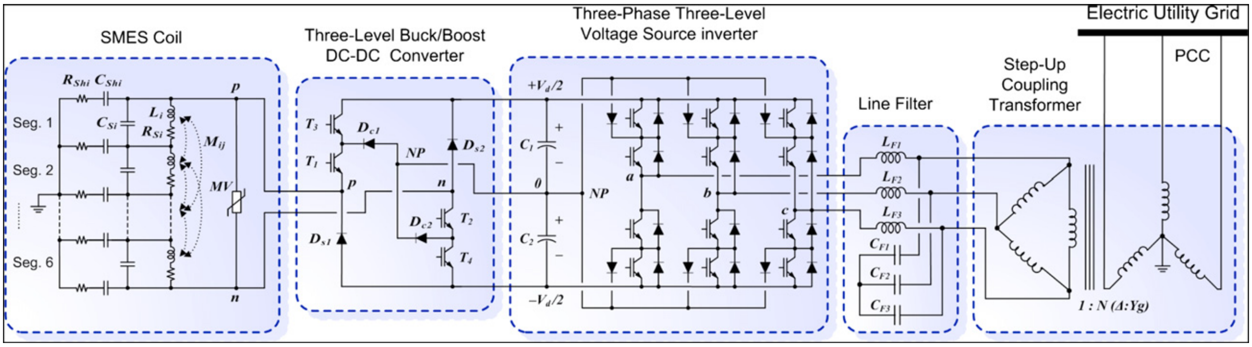

Fig. 2 – Full detailed model of the proposed DSTATCOM-SMES.

achieving a robust tuning over a wide range of frequencies while keeping the same structure. The basic idea is to separate the frequency spectra into two decoupled bands, i.e. an intermediate band and a low band, for covering respectively both small and large signal frequency disturbances.

Appropriate damping of power swings in the intermediate spectral band require from the controller a frequency response with an increasing gain from low to high bands and phase leading in the whole range of action. This condition is achieved by employing differential filters synthesized through lead–lag compensators, providing intrinsic DC wash-out, zero gain at high frequency and phase leading up to the resonant frequency. Thus, the two resulting compensators are superposed in order to obtain a combined frequency stabilizer with an adequate phase characteristic for all frequency deviation modes.

An input frequency filter is used for processing the frequency deviation signal, Δf obtained from the phase locked loop (PLL). The filter is associated with the low and intermediate bands, and guarantees a plane response in the 0–3 Hz range. In all cases, the frequency signal is derived from the positive sequence components of the AC voltage vector measured at the PCC of the DSTATCOM-SMES, through a PLL.

3.2. *Middle level control*

The middle level control makes the actual active and reactive power exchange between the DSTATCOM-SMES and the AC system, to dynamically track the reference values set by the external level. The middle level control design, which is depicted in Fig. 3 (middle side), is based on a linearization of the state-space averaged mathematical model of the DSTATCOM in *d–q* coordinates described in [7]. The dynamics equations governing the instantaneous values of the three-phase output voltages in the AC side of the VSI and the current exchanged with the utility grid can be derived in the *dq* reference frame as follows:

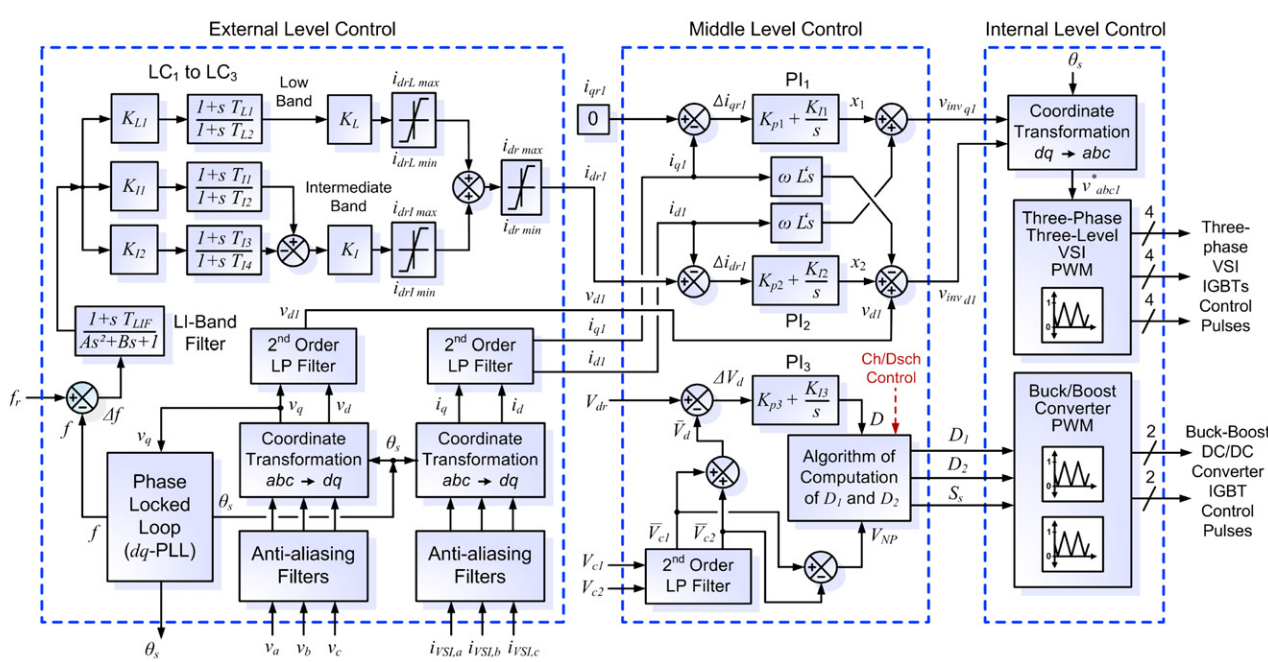

Fig. 3 – Multi-level control scheme for the DSTATCOM-SMES system.

$$s\begin{bmatrix} i_d \\ i_q \\ V_d \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_s-M} & \omega & \frac{maS_d}{2(L_s-M)} \\ -\omega & \frac{-R_s}{L_s-M} & \frac{maS_q}{2(L_s-M)} \\ \frac{-3}{2C_d}maS_d & \frac{-3}{2C_d}maS_q & \frac{-2}{R_pC_d} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ V_d \end{bmatrix} - \begin{bmatrix} \frac{|v|}{L_s-M} \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

where,

$s = d/dt$:Laplace variable, defined for $t > 0$.
ω: synchronous angular speed of the grid voltage at the fundamental frequency.
m: modulation index of the VSI, $m_i \in [0, 1]$.
$a = (\sqrt{3}/\sqrt{2})(n_2/n_1)$: turns ratio of the $\Delta - Y$ coupling transformer.
$S_d = \cos\alpha$, $S_q = \sin\alpha$: average switching factors of the VSI in the dq frame, and α the phase-shift of the VSI output voltage from the reference position.

Inspection of Eq. (1) shows a cross-coupling of both components of the DSTATCOM-SMES output current through ω. Therefore, in order to achieve a fully decoupled active and reactive power control, it is simply required to decouple the control of i_d and i_q through two conventional PI controllers, as depicted in Fig. 3. In addition, it can be seen from Eq. (1) the additional coupling resulting from the DC capacitors voltage V_d, as much in the DC side (lower part) as in the AC side (upper part). This difficulty demands to maintain the DC bus voltage as constant as possible through an extra PI compensator which allows eliminating the steady-state voltage variations at the DC bus, by forcing the instantaneous balance of power between the DC and the AC sides of the DSTATCOM through the modulation of the duty cycle D of the DC/DC chopper. Finally, duty cycles D_1 and D_2 are computed through a novel controller in order to prevent DC bus capacitors voltage drift/imbalance.

3.3. *Internal level control*

The internal level (right side of Fig. 3) is responsible for generating the switching signals for the twelve valves of the three-level VSI, and for the four IGBTs of the buck/boost DC/DC converter. This level is mainly composed of a line synchronization module, a three-phase three-level SPWM firing pulses generator and a three-level PWM generator for the IGBTs of the DC/DC converter.

4. Digital simulation results

The dynamic performance of the proposed DSTATCOM-SMES is assessed through digital simulation carried out in the MATLAB/Simulink environment [8]. The test microgrid employed to study the dynamic performance of the proposed DSTATCOM-SMES device is presented in Fig. 4 as a single-line diagram. This 12-bus power distribution system operates at 25 kV/50 Hz and includes a variety of DER units (DG based on fossil and renewable fuels and advanced DES) and different types of loads (DR). The small microgrid implements a dynamically-modeled double generator-type DG linked to a utility system. The first generator is composed of a dispatchable unit powered by a gas microturbine and includes a voltage regulator and a speed governor [9]. The second generator is made up of a variable speed wind turbine generator grid-connected through a back-to-back converter analogous to the one presented in [10]. Two sets of sheddable linear loads, grouped respectively at buses 9 and 11, are modeled as constant impedances. The proposed DSTATCOM-SMES device represents the microgrid DES and is placed at bus 4. A microgrid central breaker (MGCB) with automatic reclosing capabilities is employed for the interconnection of the point of common coupling (PCC) of the microgrid (bus 4) to the substation of the utility distribution system through a 15 km tie-line.

Three different case studies relative to basic protection and operation rules are considered, permitting to carry out both a large and a small-signal performance study of the DSTATCOM-SMES, besides the tie-line power flow stabilization and control.

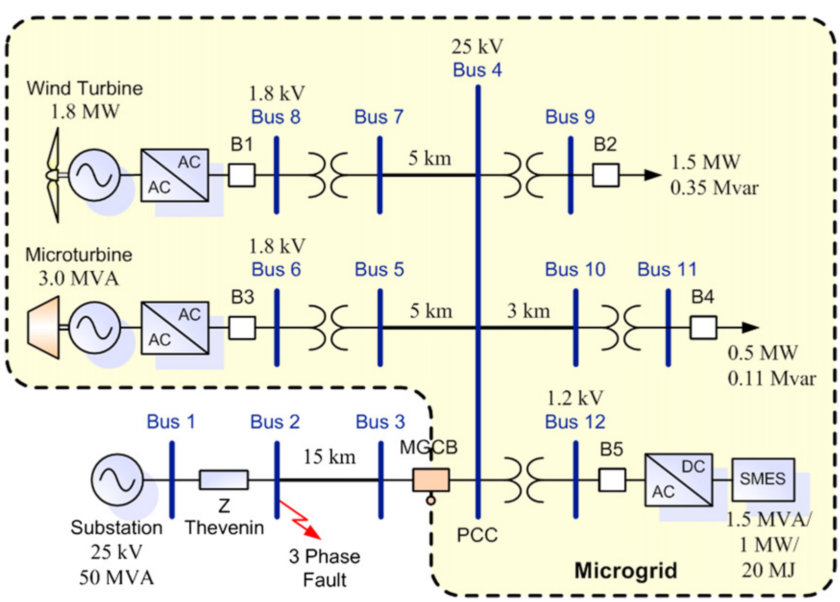

Fig. 4 – Single-line diagram of the test power system with the proposed MG.

The first case study (Scenario 1), which corresponds to a severe disturbance such as the island operation mode of the MG, considers a permanent fault which needs to be isolated by the instantaneous trip operation of the MGCB. A three-phase-to-ground fault is applied at bus 2 in the utility system at $t = 0.1$ s, and cleared 10 cycles later (200 ms) by tripping the tie-line through the opening of the main micro-grid circuit breaker. A load shedding scheme (LS) is included at all loads in order to prevent the system frequency collapse during the severe disturbance. The second case study (Scenario 2), which represents a quite less severe disturbance than the prior case, such as power oscillations (swings) damping, assumes that the fault is temporary and implements an instantaneous trip action with automatic breaker reclosing at a preset delay-time of 250 ms. The third case study (Scenario 3), considers the stabilization of the tie-line power flow when there is high penetration of wind generation. This inherently unpredictable and highly variable generation causes fluctuations of tie-line power flow which significantly affects power system operations.

4.1. *Scenario 1: assessment of microgrid operation in island mode*

One of the main goals in forming a microgrid is to maintain uninterrupted power to critical loads. Thus, the ability of a microgrid to form intentional islands is assured by appropriately operating the distributed generators located downstream of the distribution utility jointly with DES and loads. To this aim, the proposed test microgrid is intentionally forced to operate in island mode at $t = 0.12$ s and the microgrid performance during the starting of the island is analyzed through the simulation results of Fig. 5. For the configuration presented in the test case prior to the fault in steady-state, the gas microturbine is dispatched at 1.2 MW, while the wind generator is disconnected. In these circumstances the active power demanded by loads is 2 MW so that the microgrid needs to import about 0.8 MW from the main distribution system. After the fault is cleared and the tie-line tripped, the generator is operated in island conditions. Under these circumstances, the microturbine itself has to supply all the power required by loads. As can be seen from the simulation results shown in black dashed lines for this base case with no DES, the gas microturbine respond slowly. The spinning reserve of the unit is neither sufficiently large nor fast enough for supporting the system frequency and thus avoiding the microgrid collapse. The activation of the automatic LS scheme with a total load rejected of 0.8 MW is required in order to recover the system frequency to its scheduled value.

The effect of incorporating a 1 MW/20 MJ SMES coil into the DC bus of the conventional ±1.5 MVA DSTATCOM device can be studied through the simulation results of Fig. 5, shown in blue solid lines. These results clearly show the outstanding dynamic performance of the DSTATCOM-SMES. The rapid active power supply quickly absorbs the sudden power loss occurred after the tie-line tripping and thus enhances the damping of low-frequency oscillations. This condition permits to greatly decrease the power strain of the micro-generators, which results in an improvement of the reliability of the power system. In this case, the effects of the disturbance are totally mitigated in a shorter time than in the base case without being necessary to activate the load shedding scheme. The improvement of the frequency control is obtained by the immediate action of the SMES coil for supplying active power, which provides approximately 9 MJ of energy.

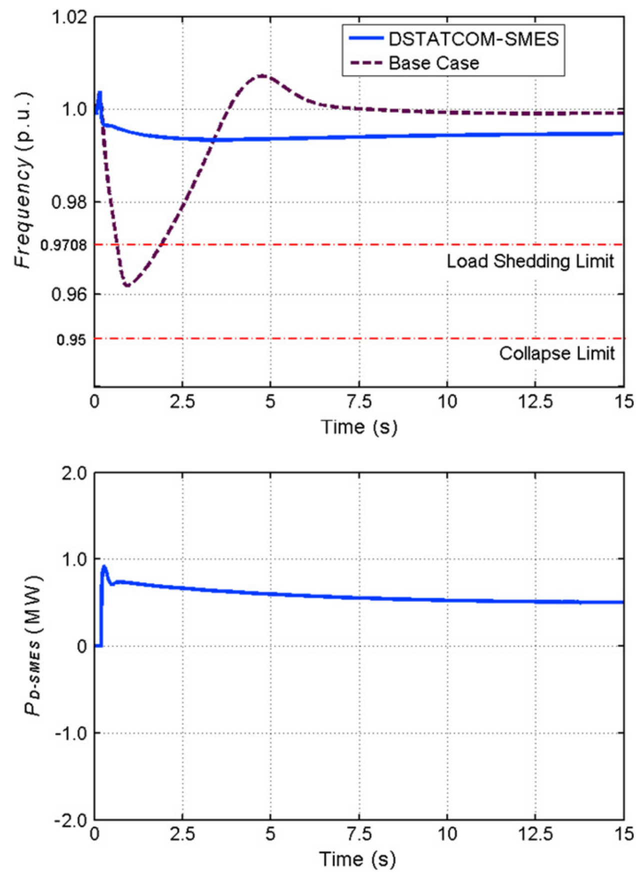

Fig. 5 – Microgrid responses to Scenario 1 (MG operation in island mode).

4.2. *Scenario 2: assessment of microgrid operation in interconnected mode to a faulted feeder*

The performance of the microgrid aiming at damping power flow oscillations in interconnected operation is now analyzed through the simulation results of Fig. 6, for the base case (i.e. with no DES) shown in black dashed lines. The disturbance occurring in the main distribution power system after the fault clearance and subsequent automatic reclosing of the breaker MGCB causes electromechanical oscillations of the gas microturbine generator. These local oscillations, between the electrical machine and the rest of the utility system must be effectively damped to maintain the microgrid stability. As can be noted from digital simulations, a local mode of approximately 2.5 Hz that settles down to its steady-state value only after 6 s is induced in the microgrid.

The effect of incorporating the DSTATCOM-SMES can be verified through the simulation results of Fig. 6, shown in blue solid lines. The transient response clearly proves the

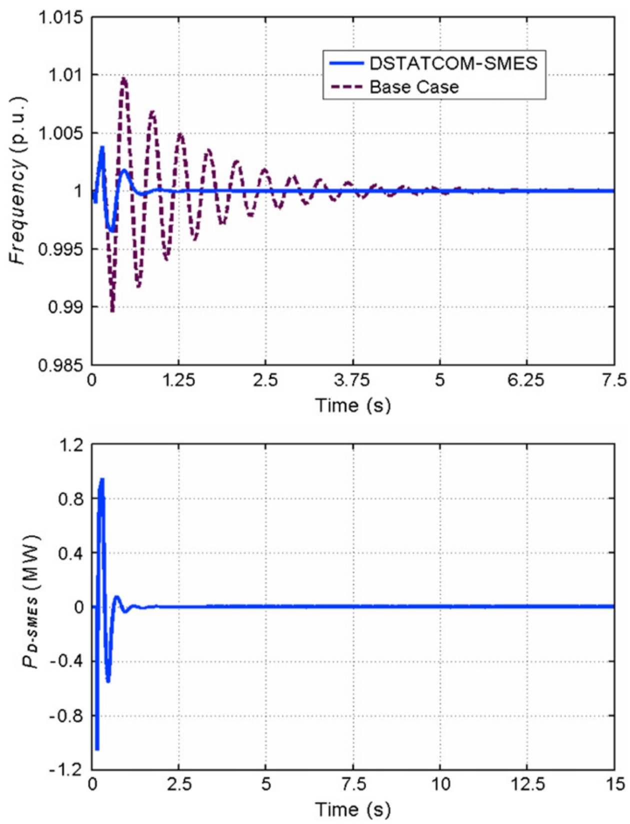

Fig. 6 – Microgrid responses to Scenario 2 (power flow oscillations damping mode).

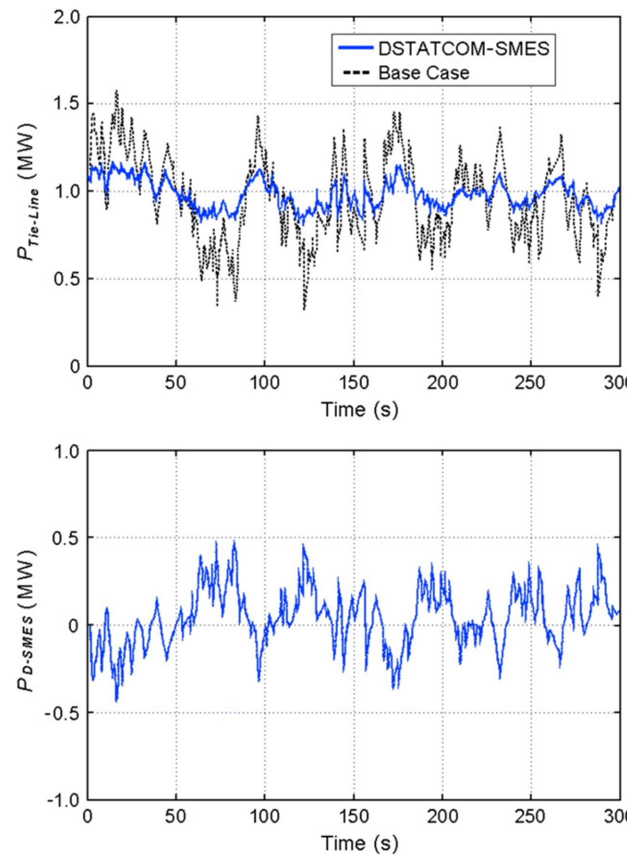

Fig. 7 – Microgrid responses to Scenario 3 (grid tie-line power flow stabilization mode).

outstanding small-signal dynamic performance of the proposed MBS controller of the DSTATCOM-SMES. The SMES unit acts as an efficient damper, absorbing surplus energy from the system and releasing energy at the appropriate time when required. The SMES unit with the proposed controller is capable of damping the oscillations in a short time and reducing the amplitude of the pulsations on the frequency considerably. In the present analysis, the settling time for the system frequency is about 1 s when the SMES unit is used for active power compensation employing the MBS. A noteworthy point is that the capacity rating of the SMES unit used in this case study for damping low-frequency power swings is only 0.15 MJ with a maximum power rating of almost 0.9 MW.

4.3. *Scenario 3: assessment of microgrid operation with huge penetration of wind generation*

The performance of the MG in interconnected operation and with high penetration of wind generation is now analyzed through the simulation results of Fig. 7, for the base case (i.e. with no DES) shown in black dashed lines. Real data of wind profile during 300 s has been measured from a real site and digitalized to represent the input of the 1.8 MW wind power generator. Under these circumstances, the microgrid tie-line to the main distribution power system is subjected to considerably changed power that significantly affects the operation of both the microgrid and the bulk power distribution system. Since the gas microturbine is disconnected in this case study, all loads are provided by the wind generator alone so that the power imported from the main utility is highly fluctuating between 0.5 and 1.5 MW.

The consequence of including the DSTATCOM-SMES can be verified through the simulation results of Fig. 7, shown in blue solid lines. The transient response clearly proves the outstanding dynamic performance of the proposed MBS of the DSTATCOM-SMES. The SMES effectively stabilize the tie-line power flow, absorbing surplus energy from the system and releasing energy at the appropriate time when required. Thus, the tie-line power flow with the DSTATCOM-SMES compensation slightly fluctuates around a 1 MW and the wind generation with DES acts as an overall near dispatchable DG-RES unit. In this way, the maximum and minimum tie-line power flow is restricted and therefore the capacity is maximized. The capacity rating of the SMES unit employed in this scenario is only around 0.3 MJ with a power rating of nearly 0.5 MW.

5. Conclusion

This paper presented an effective DSTATCOM-SMES controller used as DES of a microgrid with high penetration of wind generation. A real detailed full model and a novel multi-level control algorithm based on a decoupled current control strategy in the synchronous-rotating *d–q* reference frame with a novel controller to prevent DC bus capacitors voltage drift/imbalance were proposed. The control system employs a flexible multi-band structure controller for power damping in the frequency range of up to 3 Hz. The novel multi-level control scheme ensures fast controllability of the DSTATCOM-SMES operating in the four-quadrant modes, which enables to effectively increase the transient and dynamic stability of the microgrid.

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