Adaptive Robust SMC-Based AGC Auxiliary Service Control for ESS-Integrated PV/Wind Station

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1. Introduction

Power systems see more and more photovoltaic (PV) and wind generation integration. Within increasing renewable energy sources (RESs) penetration level, despite the advantages like environmental friendly and sustainable development, they also bring problems to the utility grid [1–3]. Adjusting power source structure brings an inevitable impact on power system primary frequency response due to the conventional generators reduction and consequent loss of inertia [4]. Therefore the provision of ancillary services is becoming an increasingly challenging task to system operation.

To deal with these issues, some grid corporation released related regulation and technical standards requesting fast frequency response from PV station and wind farm [5]. Xu et al. [6] proposed dynamic gain tuning control approach for AGC with effects of wind power. Wei et al. [7] proposed an optimal automatic generation controllers in a multarea interconnected power system with utility-scale PV plants. In general, the typical PV and wind generation operate with maximum power point tracking mode [8–10], and the corresponding control algorithms have been developed and refined along the years, being now a mature technology available in the market. It is nearly impractical to request primary frequency response from these intermittent RESs.

And the resultant damages of reserve capacity requirements from RESs are solar/wind power curtailment and lower economic efficiency.

Energy storage systems (ESSs) offer a promising capability of voltage and frequency control for power systems due to recent developments in technologies and plummeting cost [11–14]. Research work indicates that one 10 MW/3.66 MWh battery energy storage system can replace a
ESSs in practical ESS-integrated PV/wind stations face various disturbances continuously, and these uncertainties and parameter variations make accurate mathematical model building challenging. More seriously, detection limitation and time delay bring more problems to the control system. It is very difficult to achieve outstanding results by conventional SMC. Therefore, this paper proposes an adaptive robust sliding-mode control (ARSMC) system to colligate the advantages of adaptive control and SMC, eliminate the control error under various disturbances, and guarantee fast response to AGC demand, providing qualitative improvements over existing AGC auxiliary service.

2. Proposed ESS-Integrated PV/Wind Station

In this section, the construction of the proposed ESS-integrated PV/wind station is presented in Figure 1, which includes photovoltaic (PV) system, wind generation, and ESSs. The ESS-integrated PV/wind station is connected to the power grid through a circuit breaker (CB) and transformer.

Note that most PV/wind stations integrate to the utility network through cable or overhead line and the ESSs output power variations are more likely to cause voltage fluctuations or voltage sags. These problems may enforce RESs disconnection from the power grid. Therefore, it is necessary to use the ESSs to smooth active and reactive power and improve the power quality.

The ESSs can flexibly import/export power from/to the grid and compensate the power variations or reduce the power fluctuations caused by the RESs. It also can fix the station output voltage and frequency or response to power grid dispatching from AGC.

3. AGC Auxiliary Service Control

The control structure of ESS-integrated PV/wind station-based AGC auxiliary service control is shown in Figure 2. All generators in power systems operate based on daily dispatch schedule of dispatching center. Meanwhile, AGC monitor network parameters like frequency, tie-line power flow, and voltage control [39]. Morstyn et al. [40] proposed a multiagent sliding-mode control for state of charge balancing between battery energy storage systems. The switching frequency variable or chattering is an inherent problem of SMC, and many intelligent control strategies have been used to improve the conventional SMC [41, 42] and avoid chattering. Sebaaly et al. [43] proposed a constant switching frequency operation that allows chattering compensation. Wang et al. [44] proposed SMC-based ESSs to improve the controllability of the microgrid and guarantee seamless transition between its grid connected and islanded operation modes and use PWM to avoid chattering problems. Su et al. [45] developed an adaptive sliding-mode control with hysteresis control strategy for hybrid ESSs to eliminate the current fluctuating and improve its operating stability.

36 MW conventional automatic generation control (AGC) units without compromising on the AGC performance of the system for day-to-day variations experienced in the system load [15]. Using ESSs to add regulation capacity and improve dynamic performance of AGC, particularly at the high RESs penetration power systems, is a feasible solution [16–18].

Therefore, it is more practical to use commercial PV/wind generation and add extra customized ESSs to provide extra functionalities, namely, ESS-integrated PV/wind stations. The ESSs can eliminate peak and filling the through for PV/wind generation system, equip these stations with fast frequency response, and avoid voltage fluctuations and other power quality issues in the main grid. These features are important as prime movers are renewable energy sources which are characterized by having a stochastic and intermittent behavior.

Beside fast dynamic response, the ESSs are expected to have the characteristics of high control precision and strong antidisturbance capacity, along with the basic requirements like high efficiency and low output current total harmonics distortion. Many techniques have been proposed for ESSs to achieve those control objectives, including proportional-integral-derivative control, model-based control, robust control, and fuzzy control [19–24]. Most likely, traditional control technique only guarantees the desired closed-loop response at the expected operating point, and there are trade-offs between control like performances response speed, static precision, robustness, and tracking performance [25–28]. In addition, power electronic equipment and disturbance give ESSs multivariable structure and highly coupled nonlinearity which brings great challenges to conventional control techniques. Hence, it seems natural to explore other nonlinear controls that can overcome the uncertain challenges and to achieve better compensation and global stability in all operation modes.

Sliding-mode control (SMC) [29–31] is one of the most effective nonlinear robust control strategies since it provides the system dynamics with an invariance property to uncertainties once the system dynamics is controlled in the sliding mode [32, 33]. SMC has been applied to ESSs for frequency regulation [34–36], power management [37], operation state [38], and voltage control [39]. Morstyn et al. [40] proposed a multiagent sliding-mode control for state of charge balancing between battery energy storage systems. The switching frequency variable or chattering is an inherent problem of SMC, and many intelligent control strategies have been used to improve the conventional SMC [41, 42] and avoid chattering. Sebaaly et al. [43] proposed a constant switching frequency operation that allows chattering compensation. Wang et al. [44] proposed SMC-based ESSs to improve the controllability of the microgrid and guarantee seamless transition between its grid connected and islanded operation modes and use PWM to avoid chattering problems. Su et al. [45] developed an adaptive sliding-mode control with hysteresis control strategy for hybrid ESSs to eliminate the current fluctuating and improve its operating stability.

**Complexity**

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the station operation status, for example, storage surplus electricity to reduce solar/wind power curtailment. (b) Smooth RESs output power. ESSs compensate the power variations or reduce the power fluctuations caused by PV/wind generation. (c) Voltage/frequency control. ESSs fix the ESS-integrated PV/wind station output voltage and frequency.

Mode 2 is the frequency/voltage regulation response mode. ESSs generate power according to $\Delta P_{\text{ESSs}}^{\text{request}}$, quickly responding to the director of AGC.

Mode 3 is the dispatch curve follow mode. ESSs are controlled to follow the dispatch curve or to compensate PV/wind generation to decrease prediction error.

After each control cycle, ESSs feedback their status including the maximum adjustable capacity and time to LEMS. Then LEMS integrates all system parameters as adjustable capacity of ESS-integrated PV/wind station and feedback to dispatching center:

$$\Delta P_{\text{ESL}}^{\text{capacity}} = \Delta P_{\text{PV}}^{\text{capacity}} + \Delta P_{\text{wind}}^{\text{capacity}} + \Delta P_{\text{ESSs}}^{\text{capacity}} = [\alpha_j][P_N],$$

where $[P_j]$ is the rated power of each generation unit. $[\alpha_j]$ is a coefficient matrix, and $\alpha_j$ is the corresponding adjustment coefficient.

The AGC auxiliary service control is integrated with existing AGC control strategies for voltage/frequency regulation and power dispatching. Power grid dispatching center only needs to add an instruction allocation module for the ESS-integrated PV/wind station and update its coefficient matrix $[\alpha_j]$. Achieve the mutual cooperation of frequency regulation resources within fewer changes in the AGC system service modules, which is greatly engineering significant.

4. ESSs Modeling and ARSMC System

In this section, the model of the ESS in PV station and the proposed ARSMC system are presented.

4.1. ESSs Modeling. The optimization objectives of a single ESS can be summarized as follows.

Figure 3 shows the circuit topology of the ESS in ESS-integrated PV/wind station. The ESS consists of an electric battery and bidirectional DC-to-AC converter with inductor-capacitor (LC) filter connected to the AC bus together with the RESs.

In this figure, $u_a, u_b, u_c$ are the AC bus voltages (per phase) and $i_a, i_b, i_c$ are the AC currents (per phase) of the ESSs, and the converter always works symmetrically. $L_{\text{a}}, L_{\text{b}}, L_{\text{c}}$ and $C_{\text{a}}, C_{\text{b}}, C_{\text{c}}$ are the filter inductor and capacitor values, respectively. $r_{\text{a}}, r_{\text{b}}, r_{\text{c}}$ represent the equivalent resistor (ESR) of the converter, inductor, and power line. $r_{\text{fa}}, r_{\text{fb}}, r_{\text{fc}}$ represent the ESR of the filter capacitor.

The states of the switches of the $n$-th leg ($n = 1, 2, 3$) can be represented by the time-dependent variable $S_n$ and...
defined as \( S_n = 1 \), if \( T_n^+ \) is on and \( T_n^- \) is off, while \( S_n = 0 \), if \( T_n^- \) is on and \( T_n^+ \) is off.

This switching strategy, together with a small dead time generator is able to avoid internal shorts between the two switches of each bridge leg, and the switches will be in complementary states. Assuming that compared to the switches of each bridge leg, and the switches will be in synchronous rotating coordinate system, respectively.

Therefore, the dynamic equation of the ESS during the positive-half period can be represented as

\[
\begin{align*}
L \frac{d^2 e}{dt^2} &= u_a - r_i_a + \frac{s_a + s_c - 2s_e U_{dc}}{3} U_{dc}, \\
L \frac{d e}{dt} &= u_b - r_i_b + \frac{s_a + s_c - 2s_b U_{dc}}{3} U_{dc}, \\
L \frac{d e}{dt} &= u_c - r_i_c + \frac{s_a + s_c - 2s_c U_{dc}}{3} U_{dc}, \\
C \frac{d U_{dc}}{dt} &= s_a i_a + s_b i_b + s_c i_c - i_{dc}.
\end{align*}
\]

And the dynamic equation of the ESSs under dq0 synchronous rotating coordinate system can be represented as

\[
\begin{align*}
u_d &= L \frac{di_d}{dt} + \omega L i_q + r_i_d + s_d U_{dc}, \\
u_q &= L \frac{di_q}{dt} + \omega L i_d + r_i_q + s_q U_{dc}, \\
\frac{d U_{dc}}{dt} &= \frac{i_{dc}}{C} + \frac{1}{C} (s_d i_d + s_q i_q) + \omega L i_d + r_i_d + s_d U_{dc} \quad (5)
\end{align*}
\]

where \( u_d, u_q, i_d, i_q \) are the AC voltage and current under dq0 synchronous rotating coordinate system, respectively. \( u_{cond} \) and \( u_{conq} \) are the control signal under dq0 synchronous rotating coordinate system. \( L \) is the equivalent inductor, and \( C \) is the capacitor value on the converter side. \( r \) represents the equivalent series resistor of the converter, inductor, and power line. Define \( i_{refd} \) and \( i_{refq} \) as the reference of \( i_d \) and \( i_q \).

Equation (5) is rearranged as follows:

\[
\begin{align*}
L \dot{e}_d &= u_d + \omega L i_q - r_i_d - u_{cond} - L \dot{i}_{refd}, \\
L \dot{e}_q &= u_q - \omega L i_d - r_i_q - u_{conq} - L \dot{i}_{refq},
\end{align*}
\]

where \( e_{id} = i_d - i_{refd} \) and \( e_{iq} = i_q - i_{refq} \). Equation (6) is rearranged as follows:

\[
\dot{E} = a I - b U + c P I - \dot{I}_{ref}, \quad (7)
\]

where \( E = [e_{id} \cdot e_{iq}]^T, \quad I = [i_d \cdot i_q]^T, \quad U = [u_d \cdot u_q]^T, \quad U_m = [u_{cond} \cdot u_{conq}]^T, \quad I_{ref} = [I_{refd} \cdot I_{refq}]^T, \quad P = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \quad a = \omega (r/L), \quad b = -(1/L), \quad c = \omega \).

According to the aforementioned discussion, the ESSs are nonlinear, time-variable system, and there are uncertainties in the ESS-integrated PV/wind station, which are caused by parametric variations or external disturbances. Therefore, equation (7) should be modified as follows:

\[
\dot{E} = (a + \Delta a) I - (b + \Delta b) U + (b + \Delta b) U + (c + \Delta c) P I - \dot{I}_{ref} + U_m, \quad (8)
\]

where \( \Delta a, \Delta b, \) and \( \Delta c \) represent the system parameter variations and \( U_m \) represents the external disturbances or uncertainties. Define

\[
W = \Delta a I - \Delta b U + \Delta b U + \Delta c P I + U_m. \quad (9)
\]

Thus, equation (8) is rearranged as

\[
\dot{E} = a I - b U + b U + c P I - \dot{I}_{ref} + W. \quad (10)
\]

The bound of the uncertainty is assumed to meet the following inequality:

\[
|W| \leq Q, \quad (11)
\]

where \( Q = [Q_d, Q_q]^T \) represents the unknown positive constants.

4.2 ARSMC System. The proposed control system for ESSs is divided into two main parts, as illustrated in Figure 5. The first part is the primary control which produces the reference signals \( I_{ref} \) based on \( P_{req} \) and the operation mode of ESSs. The second part is the ARSMC system which generates the control signal \( U_{control} \). In this part, the state feedback term gives concise sliding surface while makes full use of
pole assignment and state feedback. Robust control term forms the structure of ESSs model. Adaptive compensation term adjusts the control law based on uncertainties or disturbance in real time. As the disturbance is unknown variables and cannot be specified or determine as a fixed value, introducing an adaptive strategy is a more practical solution.

The control objective of the ARSMC system is to make the output power of the ESSs equal to $\Delta P_{\text{ESSs}}$. Specifically, it has to enforce $i_d, i_q$ to track its reference $i_{\text{req}}$, $i_{\text{ref}}$, or enforce $I$ follow its reference $I_{\text{ref}}$.

First, define a sliding surface as equation (12), to obtain a sliding motion through the entire state trajectory, while eliminate static control error:

$$ S = E + \int (a - bK)Eds, \quad (12) $$


Second, design the control scheme as follows:

$$ U_c = U_1 + U_2 + U_3, \quad (13) $$

where

$$ U_1 = U + bKI, $$

$$ U_2 = b^{-1}(-\varepsilon \text{sign}(S)) + cPI - I_{\text{ref}}, $$

$$ U_3 = b\text{abs}(-bS)^{-1}\dot{Q}, $$

where $U_1$ is the state feedback term, $U_2$ is the robust control term, and $U_3$ is the adaptive compensation term. $\varepsilon$ is a small positive constant, $\text{sign}(S) = [\text{sign}(s_d), \text{sign}(s_q)]^T$, being $\text{sign}(\cdot)$ the sign function and $\text{abs}(\cdot)$ the absolute value function. $\dot{Q}$ is the estimated value of $Q$; define the parameter deviation as $\ddot{Q} = \dot{Q} - Q$ and the adaptive law as

$$ \dot{\ddot{Q}} = \text{abs}(-bS). \quad (15) $$

Proof. Sliding surface and parameters composing the adaptive law are based on the difference between the nominal nonlinear system and the uncertain nonlinear system, and it satisfies the global Lyapunov stability condition. Using Lyapunov stability analysis to derive the existence condition of the sliding mode and setting the Lyapunov function as

$${\dot{V}} = \frac{S^2 + \dot{Q}^2}{2} \quad (16)$$

Taking the derivative of equation (16),

$$ {\dot{V}} = SS\dot{S} + \dot{Q}\dot{Q}. \quad (17) $$

Taking the derivative of equation (12) along (9) and substituting (13) and (15) into (17) to simplify equation (17) as

$$ {\dot{V}} = S(-bU_1 + c\text{sign}(S)) + W + KE) + \dot{Q}\dot{Q} \leq \varepsilon \cdot \text{abs}(S). \quad (18) $$

Therefore, $\dot{V} < 0$ when $\text{abs}(S) \neq 0$ which ensures the asymptotically stable behavior for the sliding-mode system on the sliding surface (12).

Once the system trajectory reaches the sliding surface, it yields $S = \dot{S} = 0:

$$ \dot{S} = aI - bU + bU_1 + cPI - I_{\text{ref}} + W - aE + bKE = 0. \quad (19) $$

Deduce the equivalent control from equation (19) as

$$ U_{\text{eq}} = b^{-1}(aI_{\text{ref}} - bU + cPI - I_{\text{ref}} + W - aE + bKE). \quad (20) $$

Substitute equation (20) into equation (8):

$$ \dot{E} = aE - bKE. \quad (21) $$

It implies that probably designed state feedback coefficient $K$ guarantees the robustness of sliding mode (21) along with dynamics features like rising time and maximum overshoot.

5. Case Studies

A simulation platform under MATLAB environment based on Figure 1 is developed to validate the AGC auxiliary service performance of the ESS-integrated PV/wind station; furthermore, case studies were conducted on the NI-PXI (PCI Extensions for Instrumentation, PXI) platform to verify the proposed ARSMC system as shown in Figure 6.

The key parameters of the developed model are given in Table 1. The ESS-integrated PV/wind station in Figure 1 is connected to the grid through a 380 V/10 kV transformer. A 12 MW synchronous machine in the 10 kV grid works as a conventional regulation power source responds to AGC. According to the sliding surface (12), the control coefficient matrix is designed to guarantee the robustness of the sliding mode show as equation (21), as well as the dynamic performance and stability; set $K = [0.0180, 5]$.

The synchronous machine delivers 10 MW active power to the power grid. The ESSs in ESS-integrated PV/wind station deliver 100 kW active power to the power grid. Set dispatch instruction from AGC $\Delta P_{\text{ESSs}}$ to 500 kW to eliminate the frequency deviation. Figure 7 gives the frequency of this 10 kV power system with the synchronous
machine working as a regulation power source response to AGC, which means

\[
\Delta P_{\text{request}} = \sum_{i=1,2,3,\ldots} \Delta P_{\text{request}} + \Delta P_{\text{ESSs}},
\]

\[= 500 + 0 = 500 \text{ kW}. \tag{22}\]

Then in the same scenario, both the synchronous machine and ESS-integrated PV/wind station provide AGC auxiliary service, which means

\[
\Delta P_{\text{request}} = \sum_{i=1,2,3,\ldots} \Delta P_{\text{request}} + \Delta P_{\text{ESSs}},
\]

\[= 200 + 300 = 500 \text{ kW}, \tag{23}\]

\[
\Delta P_{\text{request}} = \Delta P_{\text{request}} + \Delta P_{\text{ESSs}},
\]

\[= 0 + 0 + 300 = 300 \text{ kW}. \tag{24}\]
In order to verify an extreme condition, PV and wind generation operate at MPPT mode and only the ESSs respond to AGC. The AGC auxiliary service control can improve the existing AGC control performance with quick response and steady state.

Figure 8 presents output power of one ESS, which is 10 kW at the beginning, and then it goes up to 40 kW response to AGC demand. Voltage and current waveforms at the AC side are shown in Figures 9 and 10. The output power falls from 40 kW to 10 kW.

In Figure 11, the output power is set to 10 kW.

In Figure 12, the voltage waveforms are shown.

In Figure 13, the current waveforms are shown.

In Figure 14, the experimental voltage waveform of the ESS is presented.

In Figure 15, the experimental current waveform of the ESS is presented.

In Figure 16, the experimental voltage waveform of the ESS is shown.

In Figure 17, the experimental current waveform of the ESS is presented.
current of the ESSs does not have any inrush spikes during the entire transition period, and there is no voltage perturbation along the operation.

Figure 11 presents the output power of one ESS, which is 40 kW at the beginning, and then it falls from 40 kW to 10 kW response to AGC instruction. Its voltage and current waveforms at the AC side are shown in Figures 12 and 13. The output current of the ESSs does not have any inrush spikes during the entire transition period, and there is no voltage perturbation along the operation.

Figures 14 and 15 show the experimental waveforms of the ESS when its output power reference is set at 10 kW. Figure 14 is the voltage waveform of the ESS at the AC side, and Figure 15 is the current waveform of phase A.

Figures 16 and 17 show the experimental waveforms of the ESS when its output power reference is set at 40 kW. Figure 14 is the voltage waveform of the ESS at the AC side, and Figure 15 is the current waveform of phase A.

These results indicate smooth and stable operation of the ESS-integrated PV/wind station and show that the ESSs provide PV and wind generation additional AGC auxiliary service functionality without changing their inner control strategies conceived for MPPT mode.

6. Conclusions

The AGC auxiliary service control proposed in this paper is integrated with existing AGC control strategies. Power grid dispatching center only needs to add instruction allocation module for the ESS-integrated PV/wind stations. It uses ESSs to add regulation capacity and improve dynamic performance of AGC without changing the control strategies of RESs conceived for MPPT mode. As the ESSs are inherently nonlinear and time variable, the mathematical model is built considering the system parameter variations and disturbances or uncertainties. The ARSMC-based ESS control system is proposed to deal these control challenges and improve its stability and dynamic performances. The rigorous proof process verifies the ARSMC strategy mathematically. The case studies on NI-PXI platform shows the fast dynamic response and robustness performance of the ESSs, guaranteeing stable operation of the ESS-integrated PV/wind station, as well as voltage and frequency regulation capability.

The ESSs provide additional AGC auxiliary service functionality without changing RES inner control strategies. The ARSMC-based ESSs is suitable for existing RESs to extend their functions and to form a ESS-integrated PV/wind station. The ESSs are independent from the use of third-party commercial RESs units, which means they do not need specific customized RESs.

Data Availability

The data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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