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 multiarea 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 RESs 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 output power of generators calculate the area control error (ACE) according to the control scheme.

Once the voltage/frequency reaches a boundary layer, a voltage/frequency regulation power is produced, and it is defined as follows:

\[
\Delta P_{\text{request}} = \sum_{i=1}^{\Sigma} \Delta P_{\text{request}, i} + \sum_{i=1}^{\Sigma} \Delta P_{\text{request}, i},
\]

where \(\Delta P_{\text{request}}\) is the total amount power demand that contains three time scales. They are \(\Delta P_{\text{request}, \text{hourly}}\), \(\Delta P_{\text{request}, \text{daily}}\), and \(\Delta P_{\text{request}, \text{monthly}}\). \(\Delta P_{\text{request}, \Sigma}\) is the power demand from conventional power plant (e.g., frequency regulation power plants). \(\Delta P_{\text{request}, \Sigma}\) is the power demand from ESS-integrated PV/wind station.

Once the local energy management system (LEMS) of the ESS-integrated PV/wind station receives the dispatch instruction or \(\Delta P_{\text{request}}\), it decomposes as
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 \( \Delta P_{\text{ESSs}} \), 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:

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

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 REs.

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. \(L_a, L_b, L_c\) and \(C_{fa}, C_{fb}, C_{fc}\) are the filter inductor and capacitor values, respectively. \(r_a, r_b, r_c\) represent the equivalent series resistor (ESR) of the converter, inductor, and power line. \(r_{fa}, r_{fb}, r_{fc}\) 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 modulation and natural frequencies, the switching frequency is relatively high. Therefore, the equivalent dynamic model of Figure 3 is obtained as shown in Figure 4, where $s$ is the Laplace operator; the power gain is defined as $k_{PWM} = \frac{U_{dc}}{u_m}$, where $u_m$ is the amplitude of a triangular carrier signal.

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

$$
L \frac{d^2}{dt^2} i_d = u_d - r_i d + s_a + s_c \cdot \frac{2s U_{dc}}{3},
$$

$$
L \frac{d^2}{dt^2} i_b = u_b - r_i b + s_a + s_c \cdot \frac{2s U_{dc}}{3},
$$

$$
L \frac{d^2}{dt^2} i_c = u_c - r_i c + s_a + s_c \cdot \frac{2s U_{dc}}{3},
$$

$$
\frac{dU_{dc}}{dt} = s_a i_d + s_b i_b + s_c i_c - i_{dc}.
$$

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

$$
u_d = L \frac{di_d}{dt} - \omega L i_q + r_i d + s_a U_{dc},
$$

$$
u_q = L \frac{di_q}{dt} + \omega L i_d + r_i q + s_a U_{dc},
$$

$$
\frac{dU_{dc}}{dt} = i_{dc} + \frac{1}{C} (s_d i_d + s_q i_q),
$$

where $u_d, u_q$, and $i_d, i_q$ 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 inductance, and $C$ is the capacitor value on the inverter side. $r$ represents the equivalent series resistor of the converter, inductor, and power line. Define $i_{ref d}$ and $i_{ref q}$ as the reference of $i_d$ and $i_q$. Equation (5) is rearranged as

$$
\begin{align*}
L \frac{di_d}{dt} &= u_d + \omega L i_q - r_i d - u_{cond} - L i_{ref d}, \\
L \frac{di_q}{dt} &= u_q - \omega L i_d - r_i q - u_{conq} - L i_{ref q},
\end{align*}
$$

where $e_d = i_d - i_{ref d}$ and $e_q = i_q - i_{ref q}$. Equation (6) is rearranged as follows:

$$
\begin{align*}
\dot{E} &= a i - b U + b U_c + c P I - I_{ref},
\end{align*}
$$

where $E = [e_d e_q]^T$, $I = [i_d i_q]^T$, $U = [u_d u_q]^T$, $U_c = [u_{cond} u_{conq}]^T$, $I_{ref} = [dref d qref]^T$, and $P = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$. $a = -(r/L)$, $b = -(1/L)$, $c = \omega$.

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

$$
\dot{E} = \dot{E}_{ref} + \dot{U}_m,
$$

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

$$
W = \Delta a I - \Delta b U + \Delta b U_c + \Delta c PI + U_m.
$$

Thus, equation (8) is rearranged as

$$
\dot{E} = a I - b U + b U_c + c P I - I_{ref} + W.
$$

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

$$
|W| \leq Q,
$$

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 $\Delta P_{request}^{ESS}$ 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 $\Delta P_{\text{ESSs}}^{\text{req}}$. Specifically, it has to enforce $i_{d}, i_{q}$ to track its reference $i_{\text{ref}d}$, $i_{\text{ref}q}$ 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 eliminating static control error:

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

where $S = [S_d, S_q]^T$ and $K = [K_d, K_q]^T$ is the control coefficient matrix.

Second, design the control scheme as follows:

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

where

$$ U_1 = U + bKI, $$

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

$$ U_3 = b\text{abs}(bS)^{-1}Q. \quad (14) $$

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

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

Therefore, $\dot{V} < 0$ when abs($S$) ≠ 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 $S = 0$:

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

Deduce the equivalent control from equation (19) as

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

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 $\Delta P_{\text{ESSs}}^{\text{req}}$ 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

\[
\Delta P_{\Sigma}^{\text{request}} = \sum_{i=1,2,3} \Delta P_{\Sigma i}^{\text{request}} + \sum_{i=1,2,3} \Delta P_{\Sigma Li}^{\text{request}},
\]

\[= 500 \, \text{kW}.\]  \hspace{1cm} (22)

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

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

\[= 200 + 300 = 500 \, \text{kW},\]  \hspace{1cm} (23)

\[
\Delta P_{\Sigma Li}^{\text{request}} = \Delta P_{\Sigma PV}^{\text{request}} + \Delta P_{\Sigma \text{wind}}^{\text{request}} + \Delta P_{\Sigma \text{ESSs}}^{\text{request}},
\]

\[= 0 + 0 + 300 = 300 \, \text{kW}.\]  \hspace{1cm} (24)

Table 1: Key parameters of ESSs and heat pumps.

| Parameter                      | Value               |
|-------------------------------|---------------------|
| **ESS parameters**           |                     |
| ESS battery size              | 50 kWh              |
| DC voltage                    | 1000 V              |
| AC voltage                    | 380 V               |
| Filter capacitance            | 3 \( \mu \)F        |
| Filter inductance             | 15 mH               |
| **Power system parameters**  |                     |
| Voltage (RMS) (phase)         | 10 kV               |
| Frequency                     | 50 Hz               |

Figure 6: The NI-PXI platform.

Figure 7: The 10 kV power system frequency.

Figure 8: Output power of the ESS (output power increases from 10 kW to 40 kW).

Figure 9: Voltage waveforms of the ESS (output power increases from 10 kW to 40 kW).

Figure 10: Current waveforms of the ESS (output power increases from 10 kW to 40 kW).
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 (Figure 11). Voltage waveforms of the ESS (output power falls from 40 kW to 10 kW) are shown in Figure 12. Current waveforms of the ESS (output power falls from 40 kW to 10 kW) are shown in Figure 13. Experimental voltage waveform of the ESS (output power is set to 10 kW) is shown in Figure 14. Experimental current waveform of the ESS (output power is set to 10 kW) is shown in Figure 15. Experimental voltage waveform of the ESS (output power is set to 40 kW) is shown in Figure 16. Experimental current waveform of the ESS (output power is set to 40 kW) is shown in Figure 17.

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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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