Event-Driven Fast Frequency Response for Energy Storage System Considering State of Charge

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Abstract. The increasing penetration of renewable energy sources reduces the equivalent inertia and spinning reserve. Power systems are becoming more and more vulnerable when subjected to active power deficits. With the trait of quick response and flexible ramp, the energy storage system (ESS) offers a promising capability to counter frequency decline after large disturbances. This paper proposes an event-driven fast frequency response (EFFR) approach for the ESS to sustain frequency stability. A centralized EFFR control framework is established, in which the wide area information is collected, and the disturbance power is broadcasted to ESSs under contingencies. Moreover, a fuzzy logic controller (FLC) is employed to determine the power set-point of the ESS based on the disturbance power and state of charge (SOC). A case study is presented to validate the feasibility and effectiveness of the proposed approach.

1. Introduction
Considering the economics and zero emissions, the renewable energy sources (RESs) are developing rapidly for energy transition. With the characteristics of volatility, randomness, and power electronic interface, the renewable generation poses great challenges to power system frequency stability [1]. Additionally, most RESs operate in maximum power point tracking (MPPT) mode and retain no spinning reserve [2]. The utilization of power electronic devices decouples the frequency between the grid side and generation side, which leads to limited equivalent inertia and primary frequency regulation (PFR). And so, the frequency dynamic response under contingencies becomes more drastic than ever before.

The energy storage system (ESS) possesses the advantage of quick response and flexible ramp, which is important to keep frequency deviation within the system operational limits. Extensive research on the application of ESSs to power system frequency control has been carried out [3]-[7]. With the combination of the time scale of economic operation and PFR, an optimal planning of the ESS and distributed generators has been established [3]. Moreover, the power set-point of an ESS is adjusted to provide frequency response auxiliary services, where a dedicated supervision algorithm for ultra-capacitor has been developed [4]. In addition, a self-tuning algorithm has been adopted for the ESS to emulate a synchronous generator [5]. And the online frequency characteristic estimator and optimization controller have been proposed to adjust the output of an ESS under significant
disturbances [6]. Furthermore, a coordinated control method for the ESS and wind turbines has been presented [7].

As for the control algorithms, the fuzzy logic controller (FLC) has been widely used [8]-[11]. The FLC has been adopted for the identification of real-time driving patterns of an electric vehicle (EV), and combined with the dynamic programming to realize self-adaptive energy management [8]. Moreover, using FLC, an autonomous thermostat has been designed for residential energy management [9]. Considering the grid frequency and the state of charge (SOC), the charging or discharging of EVs has been adjusted by an FLC [10]. The parameters of a FLC has been optimized to adjust rotor speeds for the doubly fed induction generator [11].

In this paper, an event-driven fast frequency response (EFFR) strategy is proposed for the ESS to participate in frequency stability control. The EFFR framework is presented to monitor disturbance information and assign triggering commands. The EFFR activates once a disturbance is detected, and then the triggering commands are broadcasted to corresponding ESSs. Moreover, a local FLC is deployed for adjusting the power set-point of the ESS. And the real-time SOC is taken into account, on which the operation states of an ESS are divided into three working regions. Furthermore, the bi-directional converter can change outputs promptly according to the adjusted power set-point.

The remainder of this paper is organized as follows. The establishment of proposed EFFR framework is presented in Section 2. Additionally, the ESS model for EFFR is described in Section 3. Moreover, the FLC-based EFFR control strategy is elaborated in Section 4. The case study is carried out in Section 5. And the conclusion is provided in Sections 6.

2. Centralized control framework for EFFR

The EFFR process is realized via a centralized control framework, as shown in figure 1. The phasor measurement units (PMUs) are deployed in or near terminal power facilities, e.g., generators, substations, and ESSs, to monitor their operation states synchronously. Moreover, the wide area measurement system (WAMS) collects the monitor data, and is able to attain the global information of the overall power system [12]. The collected information is stored in the data center, and the corresponding decision making is performed by the control center. To a certain degree, the EFFR control for ESSs can be regarded as one of advanced applications of WAMS.

A local area network (LAN) can be established to support transmission of data and commands. Once a specific disturbance is detected by analyzing the global information, the EFFR control activates, and the triggering commands including the collected disturbance power \( p_d \) are transmitted from the control center to the FLC of each ESS. In addition, the specific disturbances are selected. A power threshold value \( P_t \) can be obtained and updated via periodic analysis. The threshold power \( P_t \) depicts the most severe disturbance that the power system can handle without additional emergency or corrective resorts. Thus, if the disturbance power \( p_d \) exceeds the threshold power \( P_t \), the EFFR will be activated. Otherwise, there is no need for the EFFR control.

Furthermore, the local FLC adjusts the power set-point of the ESS with the received disturbance power \( p_d \) and real-time SOC as inputs. And then, the bi-directional converter takes action promptly to respond the change of the power set-point, and the ESS outputs additional power \( P_e \) to counter frequency deviation. The traits of the EFFR control for the ESS are quick response and flexible ramp. And so, the EFFR control takes action during the disturbance, and exits when the power system is transitioned into quasi-steady state.
3. ESS model for EFFR control

3.1. EFFR control model
The FLC is used to adjust the power set-point of the ESS with the disturbance power \( p_d \) and SOC as inputs. Thus, the power response process after disturbances consists of the EFFR of ESSs and the PFR of generators. The proposed FLC EFFR control model can be shown in figure 2, where \( \Delta f \) is the frequency deviation; \( \Delta p_p \) is the change of outputs of generators controlled by PFR; \( \Delta p_s \) is the additional power of the overall power system.

3.2. ESS model
The first-order transfer function \( G_E(s) \) is employed to depict the dynamics of the ESS, which can be represented as,

\[
G_E(s) = \frac{1}{1+T_Es}
\]

where \( T_E \) is the time constant considering the time delay of the commands transmission, decision making and the response of the bi-directional converter.

The SOC depicts the operation state of an ESS. If the SOC is smaller than the lower limit \( SOC_{\text{min}} \), there will be no energy can be used for EFFR control, and the ESS will exit unexpectedly. The SOC can be calculated through the integral of current. Assuming the internal voltage keeps constant, the current is proportional to the internal power \( p_{in} \). Thus, the SOC can be calculated as,

\[
SOC(t) = SOC(t_0) + \frac{1}{E_r} \int_{t_0}^{t} p_{in} (\tau) d\tau
\]

where \( SOC(t) \) and \( SOC(t_0) \) are the SOC at time \( t \) and \( t_0 \), respectively; \( E_r \) is the rated capacity of the ESS; \( \eta_{dis} \) is the discharging efficiency.

According to the SOC, the operation state of an ESS can be divided into forbidden area, suboptimal area and optimal area, as shown in Figure 3. It is obvious that the ESS cannot operate in forbidden area. Thus, in the process of EFFR control, the ESS should meet the SOC constraint, which can be expressed as,

\[
SOC(t) \geq SOC_{\text{min}}
\]

In addition, the lifetime of an ESS can be extended with more operation time in optimal area. The ESS is apt to operate in optimal area. And so, the larger the \( SOC \) is, the more additional power the ESS can provide.

Moreover, similar to the SOC constraint, the outputs of an ESS cannot exceed the power constraint, which can be expressed as,

\[
0 \leq p_e \leq p_{\text{max}}
\]

where \( p_{\text{max}} \) is the maximum discharging power of the ESS.

4. FLC-based control strategy for ESS

4.1. Fuzzification
The aim of the fuzzification block is to convert the crisp inputs into linguistic variables through membership functions. The disturbance power \( p_d \) and the SOC of the ESS are taken as the inputs for the FLC. The fuzzy sets of disturbance power \( P_d \) are labeled as zero (ZE), small (S), and large (L), respectively. In addition, the fuzzy sets of disturbance power \( P_d \) adopt trapezoidal and triangular functions, as shown in figure 4.
In addition, the variables of $SOC$ can be divided into three fuzzy sets, of which the labels are S, medium (M), and L, respectively. The trapezoidal and triangular functions are also utilized for the $SOC$, as shown in figure 5.

The output variable of the FLC is the power set-point $p_e$. Similar to the input variables, the trapezoidal and triangular functions are adopted, as shown in figure 6. The variables of power set-point $p_e$ can be divided into five fuzzy sets, whose labels are ZE, S, M, L and extra-large (XL), respectively.

![Figure 3. Different operation area of an ESS](image)

![Figure 4. The membership function of $P_d$](image)

![Figure 5. The membership function of $SOC$.](image)

![Figure 6. The membership function of $p_e$.](image)

### 4.2. Fuzzy inference

The knowledge base establishes a non-linear mapping between the inputs and outputs, which is the core part of the FLC. The input variables of the FLC correspond to the disturbance power $P_d$ and the $SOC$ of the ESS. In addition, the output variable corresponds to the power set-point $p_e$. The proposed FLC adopts the Mamdani method. Furthermore, a set of IF-THEN statements are used for knowledge base, as summarized in Table 1.

| $SOC$ | Disturbance power $P_d$ |
|-------|-------------------------|
|       | ZE          | S       | L       |
| S     | ZE          | S       | M       |
| M     | ZE          | M       | L       |
| L     | S           | L       | XL      |

### 4.3. Defuzzification

The aim of the defuzzification block is to map the outputs of each fuzzy rules into a crisp output. In the designed FLC, the centroid method is employed to obtain the crisp output $p_f$, which can be expressed as,

```math
p_f = \sum \frac{z_i \cdot \mu_{F_i}(p_f)}{\sum \mu_{F_i}(p_f)}
```
where $y_i$ and $u_c(y_i)$ are the corresponding crisp value and matching degree of the $i$th fuzzy sets, respectively; $N$ is the number of fired fuzzy rules.

4.4. Exit strategy
As for the exit strategy, a time threshold $t_s$ is set to terminate the EFFR control. In addition, a fixed droop slope $k_e$ is used to decrease the power set-point of the ESS $p_e$ gradually, and the exit time $t_e$ can be obtained as $p_e/k_e$.

5. Case study
The single-machine power system is adopted for the analysis. Moreover, an ESS with the rated power of 3 MVA and energy capacity of 10 MW·h is deployed. The parameters can be listed in Table 2. Additionally, the rating of the generator is set to 100 MVA. The simulation step is set to 0.001 s, and the simulation time is set to 30 s.

**Table 2.** Parameters of the studied power system

| $H$ (s) | $D$ (s) | $R$ | $T_K$ (s) | $K_{st}$ | $k_e$ (pu/s) | $\eta_{dis}$ (%) |
|---------|---------|-----|-----------|----------|--------------|-----------------|
| 4.0     | 1.0     | 0.05| 8.0       | 0.95     | -0.3         | 95              |
| $F_{th}$ | $T_{max}$ (%) | $T_{min}$ (%) | $T_{low}$ (%) | $T_{high}$ (%) | $p_e$ (pu) | $t_s$ (s) |
| 0.3     | 90      | 10  | 30        | 70       | 0.05         | 10              |

(a) Scenario 1
The power deficit of 0.05 pu is set to take place at 2 s. And the SOC of the ESS is set to 90%. Furthermore, the dynamic trajectories can be demonstrated in figure 7 and 8, respectively. And the results show that the proposed approach is beneficial to frequency dynamics.

![Figure 7](image1)

**Figure 7.** Dynamic response in the scenario 1.

(b) Scenario 2
The disturbance of 0.2 pu is set to occur at 2 s and the SOC of the ESS is set to 30%. The dynamic trajectories can be demonstrated in figure 9 and 10, respectively. And the results show that the proposed approach is beneficial to frequency dynamics.

![Figure 8](image2)

**Figure 8.** Power change in the scenario 1.
6. Conclusion
An EFFR approach for the ESS is proposed for the enhancement of frequency stability. A framework is presented to broadcast triggering commands to the ESS once a specific disturbance takes place. With the combination of disturbance power and SOC, a FLC is employed to adjust the power set-point of the ESS. The bi-directional converter can change outputs promptly according to the adjusted power set-point. The case study results show that the proposed approach is beneficial to frequency dynamics. In future studies, the influence of parameters on control performance will be considered.

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