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Power Electronics and Drives

Charging and Discharging Strategies for Clustered Regional Energy Storage System

Research paper

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Received: February 17, 2022; Accepted: March 03, 2022

Abstract: With the massive expansion of decentralised renewable energy in electricity grid networks, the power supply system has been changed from centralised to decentralised one and from directional to bi-directional one. However, due to the regional energy structure difference in the power imbalance between electricity generation and consumption is becoming more and more serious. A grid-scale energy storage system (ESS) can be one solution to balance the local difference. In this paper, two charging/discharging strategies for the grid-scale ESS were proposed to decide when and with how much power to charge/discharge the ESS. In order to realise the two strategies, this paper focuses on the application of fuzzy logic control system. The proposed strategies aim to reduce the peak power generation, consumption and the grid fluctuation. In particular, this paper analysis the ratio between energy-capacity and rated power of ESS. The performance of the proposed strategies is evaluated from two aspects, the normalised power of ESS itself and the influence on the power grid. Simulation studies were carried out on the rule-based control systems with different energy-to-power (e2p) ratios, and the results show that the proposed charging strategy with combination of extreme situation of power imbalance and the rest capacity of ESS provides a smooth load curve for the regional power grid system while the external power exchange is reduced effectively.

Keywords: *charging/discharging strategies • energy storage system • energy-to-power ratio • fuzzy logic control*

1. Introduction

According to IEA reports, the newly added renewable power capacity for the period of 2021–2026 is expected to be 50% higher than the period of 2015–2020 (IEA, 2021). As the usage of renewable energy sources (RES) is increasing in the electrical network system, it brings new challenges in power grid operation, stability and reliability (Al-Shetwi et al., 2020). In particular, the highly weather-dependent power generation from solar and wind energies increases the instability for power grid system, and their power generation profiles are less predictable and harmonic between power generation and consumption (Bremen, 2010; Steiner et al., 2017). Wind turbines mainly produce electricity when there is a lot of wind, and photovoltaic (PV) system can only convert solar irradiation to electricity at daytime. However, sometimes the grid cannot absorb that much electricity at all, because the amount of produced electricity exceeds the consumption and the grid capacity. So congestion becomes apparent at certain power system lines and transformers (Baltensperger et al., 2017). In order to stabilise the power grid, the transmission and distribution system operators (TSO and DSO) have to cut off the feed-in from the RES generation (Song et al., 2021; Bird et al., 2016). Another effective solution for RES application is using energy storage system (ESS) to avoid the loss of the RES energy (Park et al., 2022; Shams et al., 2021). In addition, the storage system can provide power to stabilise the grid and to minimise the fluctuation effect from RES (Rabbani et al., 1997; Wang et al., 2020).

In recent years, renewable energy generation and ESSs were widely researched. Wind-PV-storage projects were established and evaluated to achieve smooth power output and can be operated in island and grid-connected

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mode (Ren et al., 2022; Benadli et al., 2021). In Wu and Zhou (2014), a grid-connected large-scale ESS was established. It is proven that multi-agent-based energy-coordination control strategy increased the efficiency and robustness of global energy system. Fuzzy control method was used in the battery agent for the decision making. In addition, a fuzzy inference system (FIS) was proposed to control the operation of ESS in a microgrid (Teo et al., 2016). The effective control strategy resulted in better power quality and life cycle of ESS. Fuzzy control technique was also implied to satisfy the economic goals and to reduce the imbalance between cost and benefit in a hybrid grid system (El Bourakadi et al., 2020).

Significant attention has been paid on energy management for a storage system. Energy management system (EMS) based on data has been researched to reach the optimum decision-making (Mohamed et al., 2019). Using real-time data for performing energy management, optimisation of the EMS performance was achieved (Arefifar and Alam, 2019). The analysis from different perspectives, such as capacity of RESs, capacity of ESS and demand response, should be pursued in future.

In terms of intelligent energy management, the integration of power generation, load and storage assets into power grid entity was presented by Colson and Nehrir (2011). They defined the power management and control architectures to achieve cooperative behaviour amongst the grid assets. Associated storage capacity was determined according to the variation of power generation and load demands (Li et al., 2012).

Based on the fluctuating electricity generation and load, the resulting power flows are converted into a synthetic power flow with generation and consumption. In addition, a model of electricity storage in a cluster is developed. The proposed grid-connected, large scale ESS is investigated to balance the local power generation and load. In addition, two charging/discharging strategies under observation of power imbalance between generation and consumption and current state-of-charge were considered to set the operation processes of ESS. Furthermore, using real system measured data, the algorithms were simulated and evaluated. Energy-to-power (e2p) ratios instead of capacities are discussed in the further simulation procedure. To verify the efficiency of the control systems under the two charging/discharging strategies, the normalised power output and the new generated power saldo with ESS will be evaluated.

This paper is organised as follows: Section 2 describes the methodology of building one regional cluster related to the structure of an existing power network. Different charging/discharging strategies for the regional investigated ESS are then presented. Section 3 focuses on the model development. In order to realise the strategies, fuzzy control system is introduced and adapted to this unique purpose. The simulation procedures and results are presented in Section 4. Conclusions and an outlook on future works are given in Section 5.

2. Methodology

The electricity generation and loads are connected to different voltage levels. Here, we define the regional cluster related to a distribution system ranging from low to high voltage levels. Figure 1 illustrates the regional cluster. Within the cluster there are various local generations and loads. The power difference between the electricity generation and consumption was defined as power saldo here, which describes the needed power from the external grid. The power saldo can be calculated from Eq. (1). So the positive value of P_{saldo} means that, the electricity load is more than the power generation. More electrical energy should be delivered from outside power grid to the regional cluster. While there is too much power generation over the consumption, P_{saldo} value will be negative, more power generation will be exported to the neighbour or to the overlaid network.

Cluster power saldo is given by:

$$Cluster\_P_{saldo} = Cluster\_P_{load} - Cluster\_P_{generation} = \sum Cluster\_P_{feed\_lines} \tag{1}$$

where $Cluster\_P_{saldo}$ means cluster power saldo. $Cluster\_P_{load}$ represents the synthetic load at regional distribution grid system, from household sector, commerce, trade and services sector to industry sector. $Cluster\_P_{generation}$ means power generation in cluster area, which mainly contains renewable power generation from PV, wind and other generations, such as biomass and gas power plant. $Cluster\_P_{feed\_lines}$ means the feed-in power from the connected power substations.

Electrical ESS is defined and used in this study to modify the influence of regional renewable energy generation. It can reduce the fluctuation of the generation and load, and the transmission congestion can

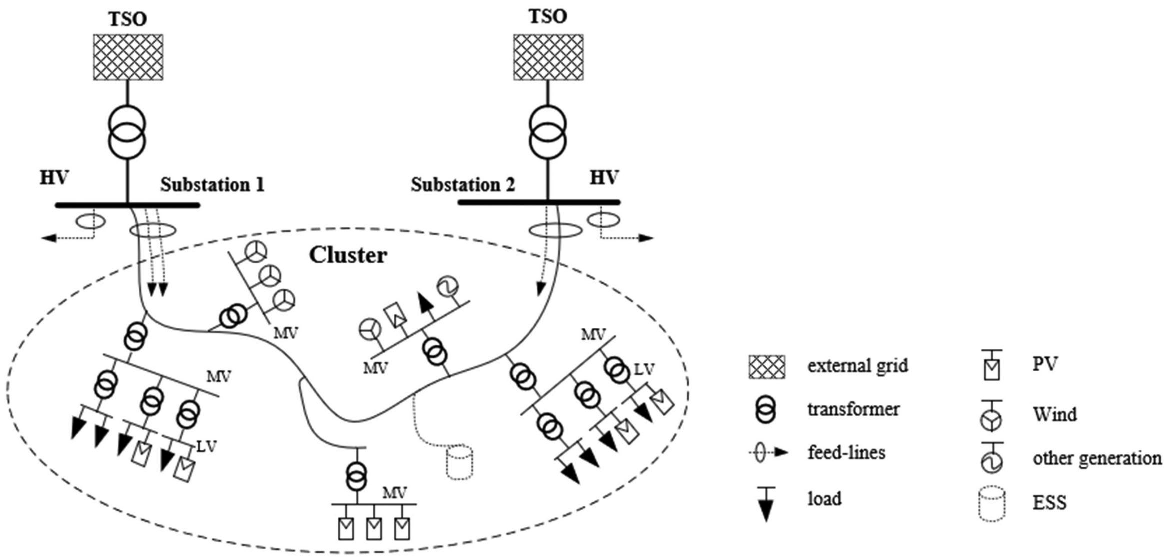

Fig. 1. Regional cluster. ESS, energy storage system; PV, photovoltaic; TSO, transmission system operators; HV, high voltage; MV, medium voltage, LV: low voltage.

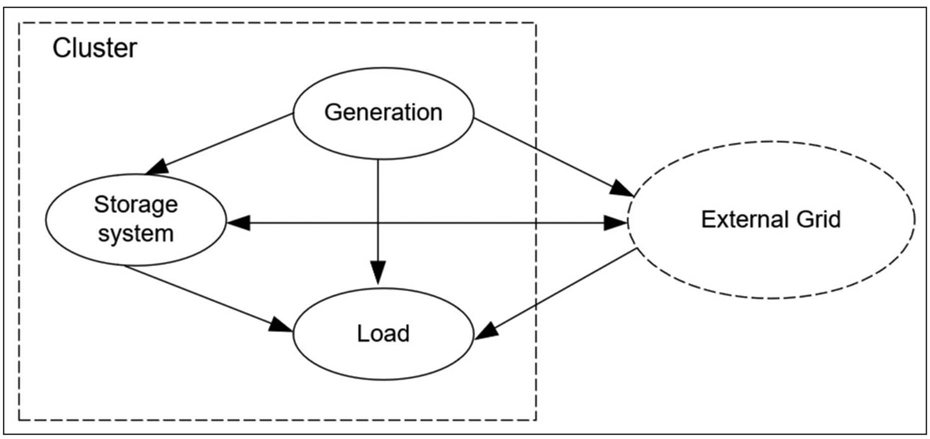

Fig. 2. Energy storage in power supply system.

be reduced through the investigated ESS as well (Vargas et al., 2015). The high power imbalance between generation and load requires an ESS to ensure the optimal operation of the power grid. It is necessary to reduce the peak of the power saldo. With the investigation of ESS, the new generated power saldo can be formed [Eq. (2)]. Figure 2 illustrates a simplified power supply with ESS. The virtual ESS can store the regional surplus energy when the supply is higher than the demand. The ESS provides the energy to the local grid when the supply is less.

$$Cluster\_P_{saldo\_new} = Cluster\_P_{load} - Cluster\_P_{generation} + Cluster\_P_{ess} \tag{2}$$

The virtual ESS is understood here as a battery model with charging and discharging process. Additionally, the storage system is characterised chiefly by its storage capacity and rated power. In this paper, the e2p ratio is used and defined in Eq. (3). The rated energy capacity (E_{cap} in MWh) is divided by the rated power output (P_{rated} in MW), thus we get the duration time (e2p in h) for charging or discharging. The e2p ratio describes how long the storage system can be operated at its rated power (Hesse et al., 2017). State-of-Charge (SoC) represents

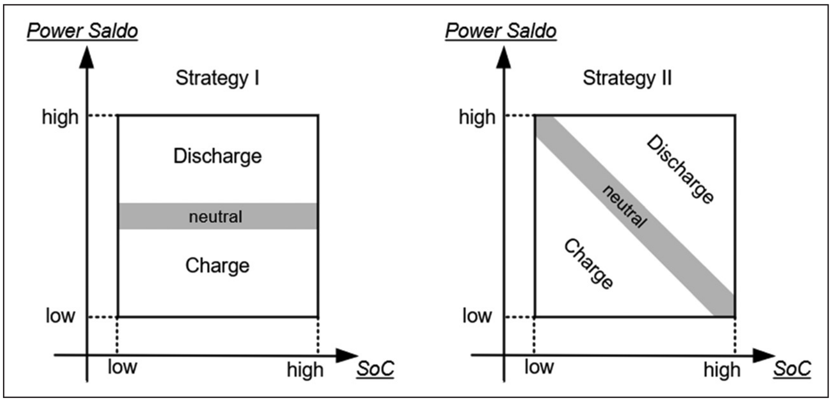

Fig. 3. Charging/discharging strategies for a storage system. SoC, State of Charge.

the available capacity utilisation of the ESS, which 0% means empty and 100% means full. After the charging/discharging process, the new SoC will be then formulated according to Eq. (4).

$$e2p = \frac{E_{cap}}{P_{rated}} \tag{3}$$

$$SoC(t+1) = \frac{E(t+1)}{E_{cap}} = \frac{E(t) + \Delta E(t)}{E_{cap}} \tag{4}$$

where $E(t)$ is the current capacity of the ESS and $\Delta E(t)$ represents the amount of charging/discharging energy.

The charging/discharging strategy could be used to manage the operation mode of ESS based on power saldo. Two charging/discharging strategies were illustrated in Figure 3. Strategy I was used to discharge the ESS during the peak time of power saldo, and during the off-peak time, the ESS was charged to reduce the peak power. When the power saldo is neutral, then no operation is undertaken in ESS, which means neither charging nor discharging happens. Strategy II considered the current situation of SoC. The storage system should be operated with higher power rate at the extreme situation of the grid. From this aspect, the ESS should be charged when the power saldo is low or negative with surplus energy and discharged at a higher value of power saldo by lack of energy.

The operation power of ESS can be scaled into interval [−1, +1] field with the implementation of normalised power of ESS $p_c(t)$, and it is formed in Eq. (5). The positive normalised power represents the charging process and the negative normalised power indicates the discharging process of the storage system. $P_{ess}(t)$ is the operation power at timestamp t. The SoC for the next time step is formulated in Eq. (6) with the implementation of e2p ratio and normalised power $p_c(t)$. Δt indicates the charging or discharging time.

$$p_c(t) = \frac{P_{ess}(t)}{P_{rated}} \tag{5}$$

$$SoC(t+1) = \frac{E(t) + P_{ess}(t) * \Delta t}{E_{cap}} = SoC(t) + \frac{p_c(t) * \Delta t}{e2p} = f\left(SoC(t),\, p_c(t)\right) \tag{6}$$

3. Model Development

In order to realise the charging/discharging strategy for virtual storage system, the fuzzy logic control was implemented in this study. Fuzzy logic control can define the operation power rate quite well. Figure 4 shows the basic configuration of FIS. First, the input parameter will be fuzzified according to the fuzzy set. Second, rules are set and combined with inference control system. Finally, in this work, the Mamdani defuzzification method is used to find the centroid of the distribution (Hossain et al., 2013). The output values are set as the normalised power of

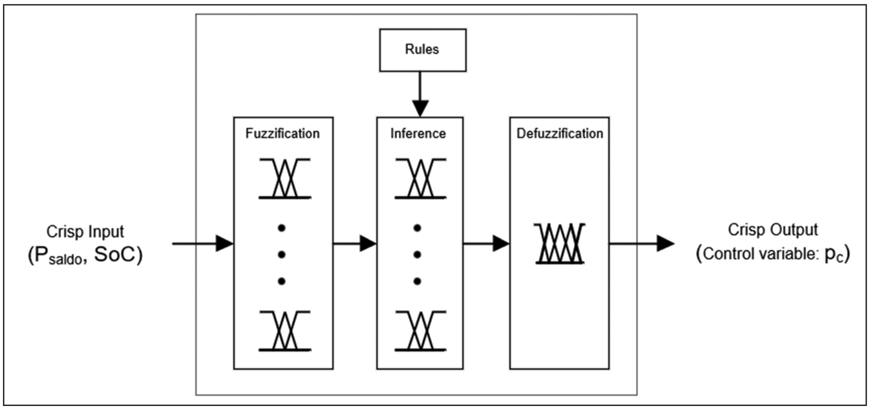

Fig. 4. Basic configuration of a fuzzy system. SoC, State of Charge; Pc, normalised power.

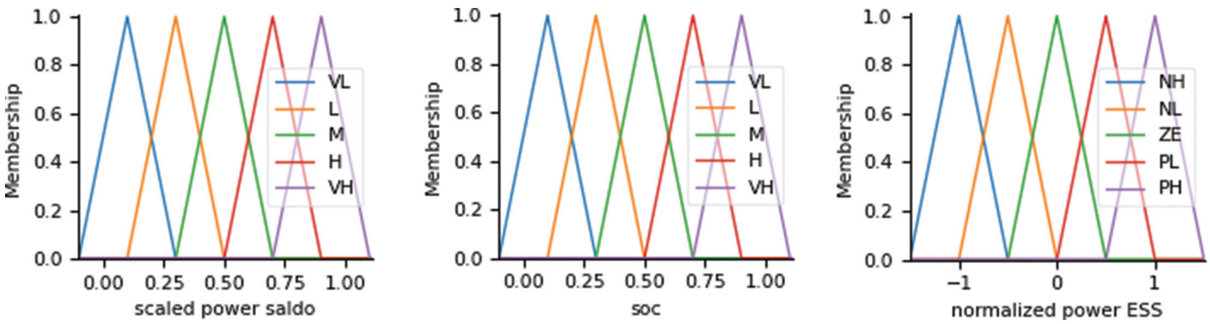

Fig. 5. Input/output membership functions. ESS, energy storage system; SoC, State of Charge.

the storage system. The fuzzy system controller has two inputs and one output. The simulation of the proposed model architecture is realised in SciKit-Fuzzy (Skfuzzy, 2022), which is one fuzzy logic toolbox integrated in Python computing language.

3.1. Membership function

During the data fuzzification, the membership functions are created. The membership function assigns the parameter into graded levels into fuzzy set. It determines the degree of the variable of each element. Before defining the membership function, the parameter should be pre-processed. In this work, the triangular function was used to generate the input and output membership functions. With the aid of a min-max feature scaling, the input parameter is valued in the interval range [0, 1]. Here we use the scaling process for the power saldo.

The transformation process for parameter is given by:

$$X_{scaled} = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{7}$$

The membership function of input parameters and output rules function of normalised power are shown in Figure 5. The centroid of class area represents the typical value of it. The description of the fuzzy sets is explained in Tables 1 and 2, in which the input parameters were classified into five groups, from very low to very high. The output power was graded into five levels with positive and negative characteristics. The negative power output means discharging of the storage system and positive power output means charging of the storage system.

3.2. Fuzzy control system

The normalised power output of the storage system can be determined based on the fuzzy control system. The FIS is a matrix of the 'if-then' rules. The conditional statements are presented in Table 3. For example, if the power saldo

Table 1. Input fuzzy sets description

ID	Membership	Description	Scaled value (%)
1	VL	Very low	10
2	L	Low	30
3	M	Medium	50
4	H	High	70
5	VH	Very high	90

Table 2. Output fuzzy sets description

ID	Rules	Rule description	Normalised power output
1	Rule NH	Rule negative high (discharging)	$p_c = -100\ \%$
2	Rule NL	Rule negative low (discharging)	$p_c = -50\ \%$
3	Rule ZE	Rule zero (no operation)	$p_c = 0\ \%$
4	Rule PL	Rule positive low (charging)	$p_c = +50\ \%$
5	Rule PH	Rule positive high (charging)	$p_c = +100\ \%$

Table 3. Conditional statements for control systems

Control system 1						Control system 2					
Saldo \ SoC	VL	L	M	H	VH	Saldo \ SoC	VL	L	M	H	VH
VH	NH	NH	NH	NH	NH	VH	ZE	NL	NL	NH	NH
H	NL	NL	NL	NL	NL	H	PL	ZE	NL	NL	NH
M	ZE	ZE	ZE	ZE	ZE	M	PL	PL	ZE	NL	NL
L	PL	PL	PL	PL	PL	L	PH	PL	PL	ZE	NL
VL	PH	PH	PH	PH	PH	VL	PH	PH	PL	PL	ZE

SoC, State of Charge.

is VH and SoC is VH, then the ESS is in discharging mode and discharged with power level NH. Corresponding to the two charging/discharging strategies, here we define the two control systems that are assigned with different conditional statements. In addition, SoC is under the constraint of Eq. (8), where SoC_{min} is corresponding to VL = 10% and SoC_{max} is set as VH = 90%.

$$SoC_{min} \le SoC(t) \le SoC_{max} \tag{8}$$

3.3. Assessment

To evaluate the effectiveness of the investigated virtual, cluster-related ESS with fuzzy control system, there are four items under two aspects (Table 4) from ESS itself and its influence for the power grid to be compared in this paper. The maximum and minimum power saldo with/without ESS are obtained from the simulation results, to see how much the peak power will be reduced.

According to the power supply quality, the power gradient amplitude in 15-min will be taken into consideration. The 15-min deviation of normalised power ESS describes how fast the storage system can be operated at a certain gradient amplitude. The 15-min deviation of power saldo represents the degree of change in required power from external grid. The assessment aspects are shown in Table 4.

Table 4. Assessment items

Aspects	Items	Symbol
ESS	Normalised power ESS	$p_c(t)$
	15-min deviation of normalised power ESS	$\Delta p_c(t) = p_c(t) - p_c(t-1)$
Power grid	Power saldo with/without ESS	$P_{saldo}(t)$
	15-min deviation of power saldo with/without ESS	$\Delta P_{saldo}(t) = P_{saldo}(t) - P_{saldo}(t-1)$

ESS, energy storage system.

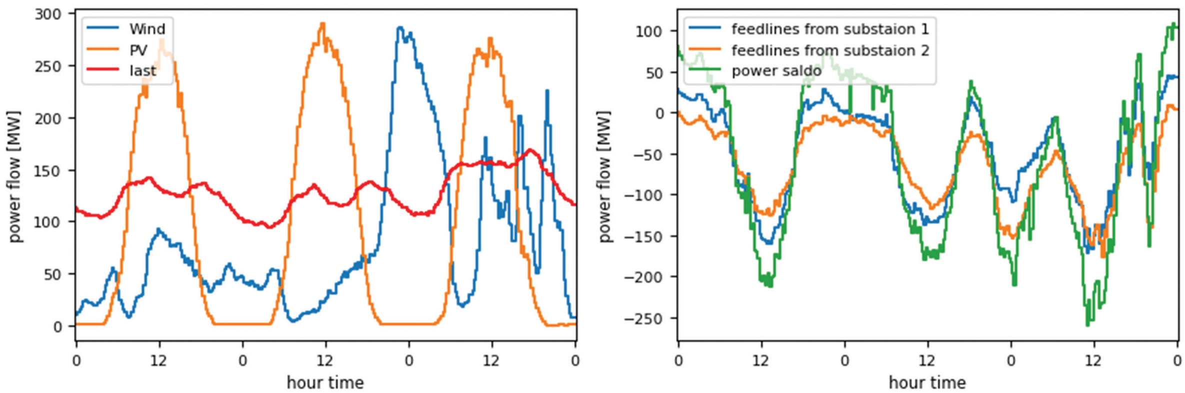

Fig. 6. Profiles of load and generation (left) and profiles of power feedlines and power saldo (right). PV, photovoltaic.

4. Simulation and Results

The data used in the simulation are real and were obtained from the regional distribution system operator. With the measurement of the high voltage feed lines for the regional supply system, the regional power saldo data were then generated. The regional installed capacities of PV and wind in distribution network are 365 MW and 710 MW, respectively. The profiles of synthetic load situation and renewable power generation are shown in Figure 6. The regional cluster is supplied from two substations and the power flow of feedlines from the substations is plotted in Figure 6. The power saldo was derived from these power flows. The 3-day sampled data for the regional network cluster were used for simulation. The sampled data had 15-min resolution. The high negative power saldo indicates the high potential utilisation of the surplus energy for the regional network cluster. The surplus power reaches >250 MW.

The procedure of the proposed simulation of the fuzzy logic control is shown in Figure 7. It can be found that the FIS was under two control systems, which represent the two charging/discharging strategies. After getting the output from each fuzzy control system, the power output of ESS will be derived from the normalised power with rated power, which is set as 100 MW. The capacity of the storage system is determined from the e2p ratio.

To obtain the new SoC in the next time step, the selection and setting of the e2p ratio and control system play crucial roles. Thus, the SoC is generated from the normalised power and e2p ratio based on Eq. (6). The operation time Δt in this study was set as same as the row data time resolution of 15-min. The initial SoC for the simulation was set at medium level M = 0.5.

In case studies, we simulated the three different e2p ratios (1, 5, 10) combined with two charging/discharging strategies. Figures 8 and 9 show the normalised power of ESS and SoC by different e2p ratios, respectively. The two control systems can charge/discharge ESS. From the normalised power curve of ESS, it can be seen that the ESS under control system 2 is more sensible. Control system 1 charges and discharges the ESS with a higher

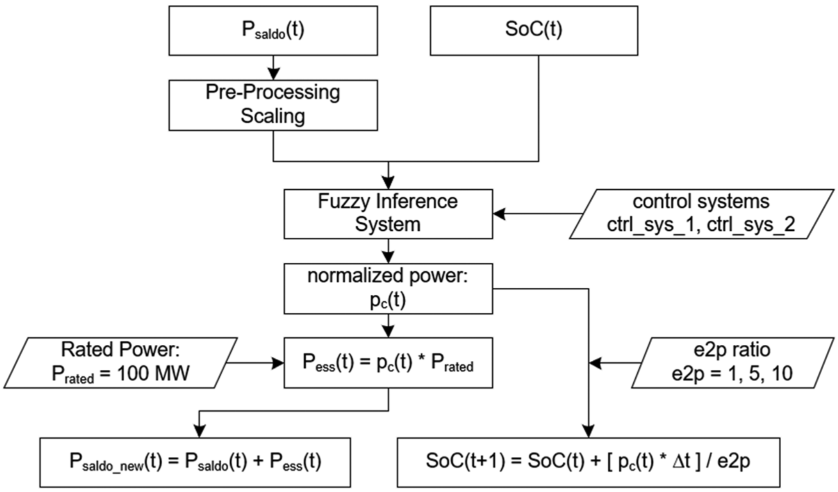

Fig. 7. Procedure of the proposed simulation. SoC, State of Charge.

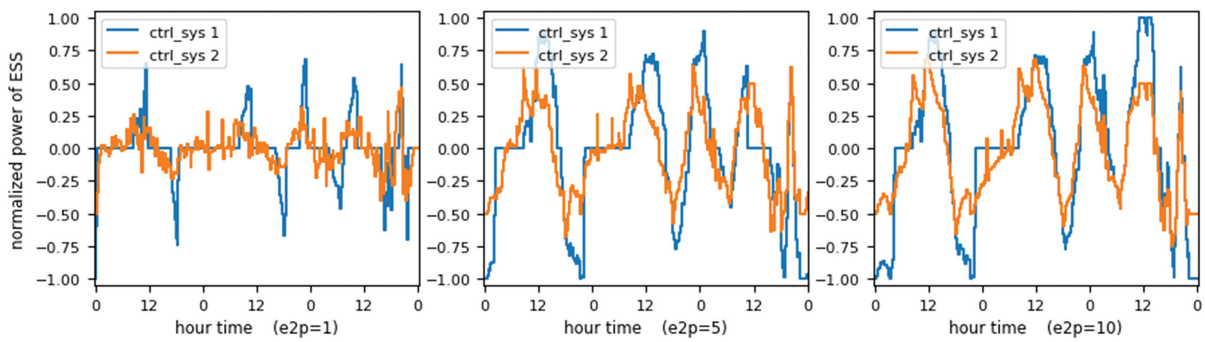

Fig. 8. Normalised power output profiles. e2p, energy-to-power.

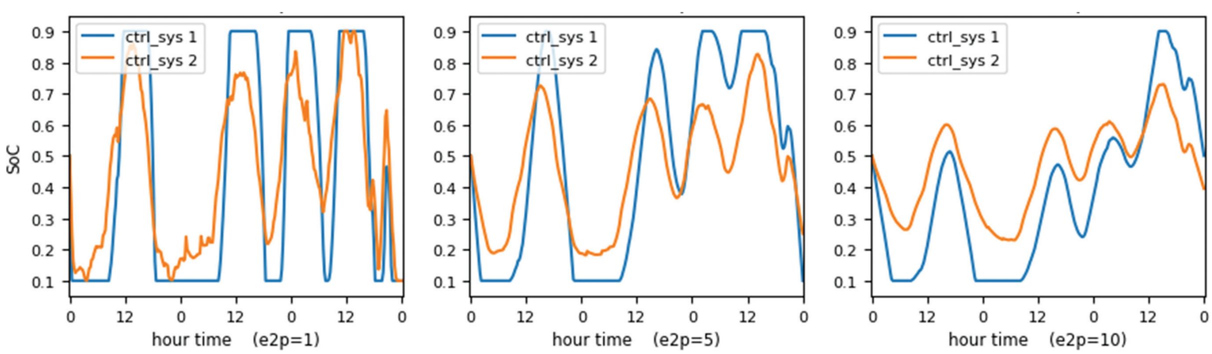

Fig. 9. SoC of ESS. ESS, energy storage system; e2p, energy-to-power; SoC, State of Charge.

power rate and the ESS can reach its maximum or minimum SoC faster due to its control rules for PH and NH as in Table 3. However, the ESS is unable to be operated when it reaches its SoC limits, and it has to wait for the next available charging/discharging signal. It can be noted that outcome from the control system 2 with e2p = 5 does not have much difference from the system with e2p = 10.

Considering the dynamic range of SoC in Figure 9, the capacity of ESS tends to be stable in a smaller range when a bigger capacity was implied. Higher depth of discharging has negative impact on the life cycle of ESS

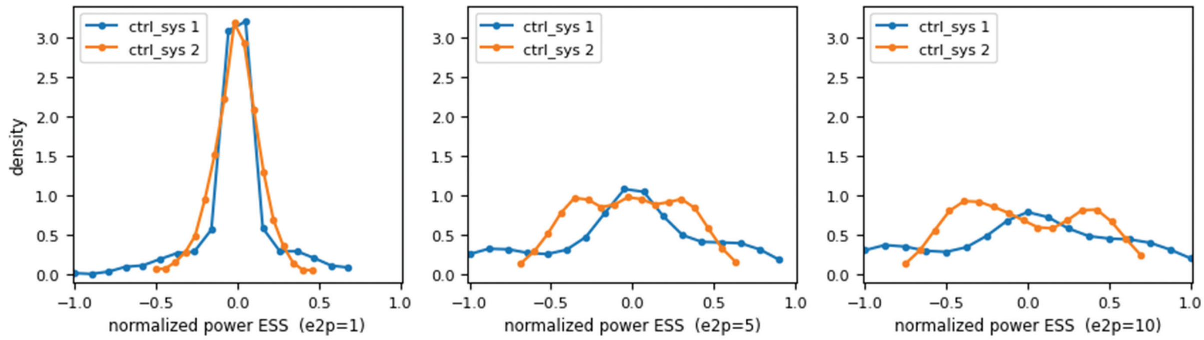

Fig. 10. Distribution of normalised power ESS. ESS, energy storage system.

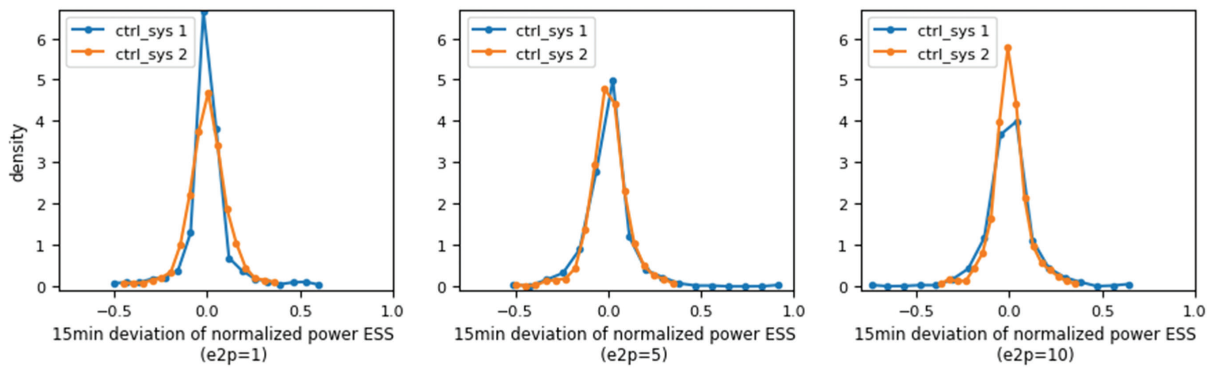

Fig. 11. Distribution of 15-min deviation of normalised power ESS. ESS, energy storage system; e2p, energy-to-power.

(Teo et al., 2016). The extreme status of rest capacity can be avoided with control system 2. The SoC of ESS with e2p = 10 is kept within a range of 0.25–0.7.

Descriptive statistics is used for the assessment of results. It can be found in Figure 10 that ESS under control system 1 can be operated at rated power. ESS under control system 1 with e2p = 1 can be only charged or discharged at the rate of 50%. With bigger e2p ratios, both control systems can operate the ESS with a higher power rate. The reason is that the higher e2p ratio means higher capacity of the ESS and SoC changes not very big with the same operating power. During the times of high-power demand in the grids and when the ESS is still near-fully charged, the ESS can deliver high rate of power to the grid system.

As shown in in Figure 11, the 15-min deviation of normalised power for control system 2 distributed in the range of −0.5 to 0.5, and the power change of ESS under the control system 1 is bigger than control system 2. No extreme charging/discharging power gradient is required for the ESS, when it is near-fully charged or discharged under the intelligent control system 2.

In Figure 12, the power profiles show the power saldo results with ESS in comparison to the power saldo without ESS. It is noticeable that the both control systems can match the high power saldo. Neither of the investigated control systems can reduce the peak power very well under e2p = 1. But ESS with bigger e2p ratio gives a better performance.

Figure 13 shows the overall distribution profiles of power saldo. A bimodal distribution of power saldo with positive and negative values implies that this region is a consuming and productive area. By focusing on the maximum and minimum values, we can find how much peak power is reduced in terms of different control strategies and e2p ratios. Both control systems deliver a better result in positive peak power shaving. When e2p = 1 and e2p = 5, the peak feed-back power (in negative) is not reduced by control system 1. That is because before the maximal surplus power occurs, the ESS is already fully charged in advance.

It can be found by comparing the 15-min deviation of power saldo with/without ESS (Figure 14) that the control system 1 aggravates the gradient of the power saldo. Aggregated power flows from generation and consumption

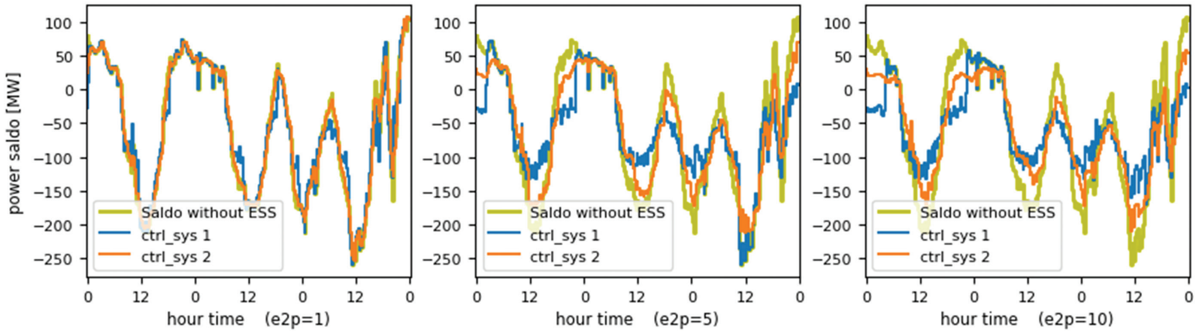

Fig. 12. Power saldo profiles with/without ESS. ESS, energy storage system; e2p, energy-to-power.

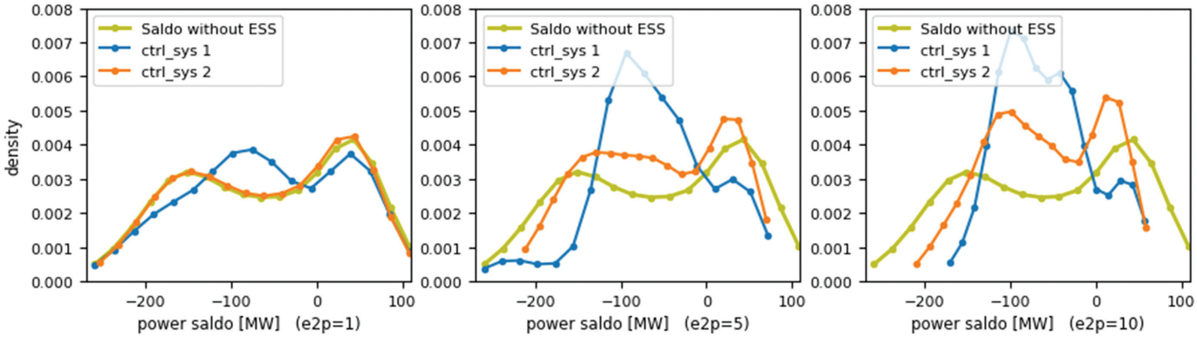

Fig. 13. Distribution of power saldo with/without ESS. ESS, energy storage system; e2p, energy-to-power.

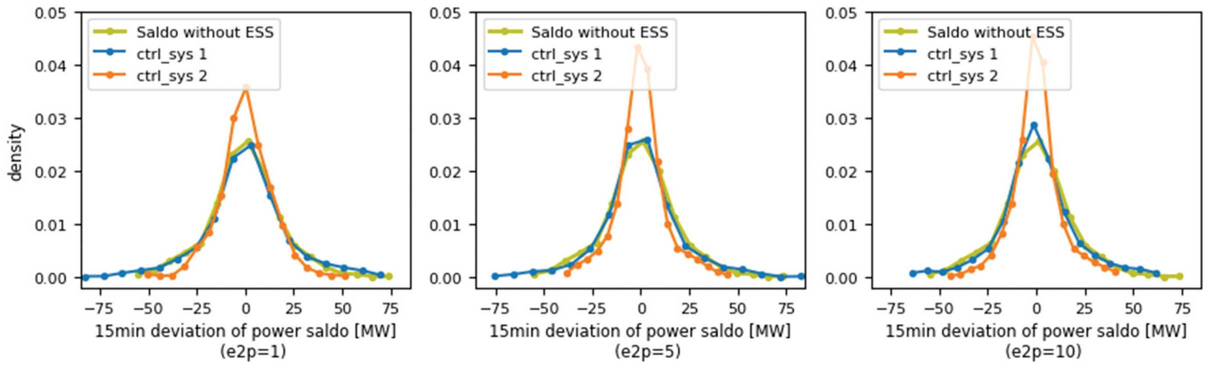

Fig. 14. Distribution of 15-min deviation of power saldo with/without ESS. ESS, energy storage system; e2p, energy-to-power.

can be smoother under the control system 2. As a result, the frequent charging/discharging has great influence on the stability of power exchange with external grid. Therefore, the combination of observation of power saldo and status of ESS can give a better decision strategy for ESS. The ESS is controlled not to be operated at a sudden high-power rate to avoid a high power change in the power system. It contributes to the stability of the grid.

The calculated power saldo profile provides insights into the investigation of the ESS. The new investigated ESS can provide a smooth power curve based on the fuzzy control system. But if the rest capacity of ESS is not considered (charging strategy I), the investigation of ESS may bring new challenges in power system. The unexpected high-power deviation may occur. However, high-power gradient of power saldo can also be avoided through the implement of ESS under control system 2, which combines the power grid generation and consumption situation and status of ESS. ESS provides higher rate of power only when power demand is high and the ESS is near-fully charged.

5. Conclusions

The idea of regional cluster was introduced along with a fuzzy approach to power saldo management. The proposed energy system model, which consists of four sub-models, was presented and discussed in detail. The supply-dependent electricity generation and demand were closely observed for the investigation of regional electricity surplus. The investigations of the regional load and power generation are carried out based on the reduced network cluster.

Charging/discharging strategies for virtual ESS were proposed and evaluated. The fuzzy logic application was then proposed for the strategies and worked well. The regional power saldo and SoC of ESS were set as input data to manage the local investigated ESS. The normalised power output combined with a rated power and different e2p ratios were comprehensively discussed. After the comparisons, we found that the control strategy with observation of the grade of power saldo and its own current capacity can be better implemented for intelligent control ESS. With a higher e2p ratio, strategy I has a better performance in terms of reducing peak power. But due to its higher power rate, it brings more challenge in the stability of the power exchange with external grid. Extreme power requirement for fast fully charged or discharged ESS is avoided under the charging/discharging strategy II. Smooth power saldo profile will be then achieved.

These useful and impressive results encourage more research activities in multiple inputs and charging/discharging strategies. It should be possible for controller to generate effective control rules under different pre-processing, such as standard scaling, robust scaling, and new membership functions from experience.

Author Contributions

YL – Research concept and design; Collection and/or assembly of data; Data analysis and interpretation; Writing the article; Final approval of the article. PJ – Research concept and design; Critical revision of the article; Final approval of the article. KP – Research concept and design; Critical revision of the article; Final approval of the article. HS – Final approval of the article.

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