CHAPTER V

BESS VOLTAGE REGULATION CONSIDERING SoC RESTORATION

5.1 Introduction

This chapter proposes a management strategy for SoC Restoration of BESS to eliminate saturation concerns and produce optimal VD in ADN. It begins by presenting an overview technique for calculating SoC Restoration and control strategies. Then the chapter defines the objective function for evaluating the effectiveness of the suggested solutions and includes numerous case studies that demonstrate the practical application of SoC restoration in real-world circumstances.

Effective management of SoCs can greatly enhance voltage profiles and minimize voltage drift by using advanced control methods and optimization techniques. The insights shared here play a vital role in the ongoing conversation about enhancing the stability of today's energy networks, particularly as we see a rise in the use of renewable energy sources.

5.2 SoC Restoration Formulation

SoC restoration is the process of bringing the SoC level back to the nominal level to enable more efficient operation.

From equation Eq. (4.1), the equation for the discharge and charge of the BESS can be rewritten considering SoC restoration, as shown in Eq. (5.1).

$$P_{BESS} = P_{BES} + P_{SoC} \tag{5.1}$$

The principle is to check the remaining SoC level compared to the nominal SoC as follows: If the SoC is between 0 and 0.45, the battery will charge to increase the SoC level for future operations. Meanwhile, if the SoC is between 0.55 and 1, the battery will discharge to prevent the SoC level from becoming too high and causing battery saturation. This operation can be represented by Eq. (5.2) and Eq. (5.3).

$$P_{SoC,d} = \begin{cases} 0 & \text{if } 0 < \text{SoC} < 0.55 \\ \dfrac{P_{SoC,\max} P_{SoC,\min} e^{n_{ds}(SoC-0.5)}}{P_{SoC,\max} + P_{SoC,\min} e^{n_{ds}(SoC-0.5)} - 1} & \text{if } 0.55 < \text{SoC} < 1 \end{cases} \tag{5.2}$$

$$P_{SoC,c} = \begin{cases} 0 & \text{if } 0.45 < \text{SoC} < 1 \\ \dfrac{P_{SoC,\max} P_{SoC,\min} e^{n_{cs}(0.5-SoC)}}{P_{SoC,\max} + P_{SoC,\min} e^{n_{cs}(0.5-SoC)} - 1} & \text{if } 0 < \text{SoC} < 0.45 \end{cases} \tag{5.3}$$

$$P_{SoC} = \begin{cases} P_{SoC,d}, & \text{discharge} \\ P_{SoC,c}, & \text{charge} \end{cases} \tag{5.4}$$

As shown in Equation (4.8), after the voltage deviation has been reduced, the BESS aims to maintain its SoC within an appropriate range typically between 0.45 and 0.55 for effective voltage control. This consideration allows the BESS operation to be further modeled and integrated into the NRLF analysis. Consequently, the bus voltage can be recalculated with this updated model, as expressed in Equation (5.5).

$$P_{BESS} + P_k^{gen} - P_k^{load} - \sum_{j=1}^{n} [V_k V_j (G_{kj} \cos\theta_{kj} + B_{kj} \sin\theta_{kj})] = 0 \tag{5.5}$$

5.3 Objective Function

5.3.1 PSO Based TSoC Improvement

In this study, an additional objective function will be introduced to maintain the SoC level at the nominal level. The objective function used in the study is illustrated in the following equation.

$$\text{minimize } \mathrm{T}SoC = \sum_{k=1}^{N} \left(\left| SoC_k - SoC_0 \right| \right) \tag{5.6}$$

This objective is to reduce the sum deviation of SoC from the nominal level. Reducing this deviation will allow BESS to control the voltage continuously, thereby improving the system's performance. The working equation of PSO is following Eq. (3.12) and Eq. (3.13). where x_i is the population of particles that represent the adjust exponent of $P_{SoC,d}$ and $P_{SoC,c}$, which are n_{ds} and n_{cs}, respectively. The proposed PSO computational procedure is illustrated in Fig 5.1.

5.3.2 PSO Based TVD Improvement

From Eq. (4.9), the equation is as follows:

$$\text{minimize TVD} = \sum_{k=1}^{N}(V_k - V_0) \tag{5.7}$$

The proposed PSO computational procedure is illustrated in Fig 4.5. The constraints are defined as follows Eq. (4.10) – Eq. (4.16).

5.4 FMOO-based PSO

In this study, the FMOO-based PSO algorithm uses a linear Max-Min method. This approach sets the boundaries using the maximum and minimum values of each objective, creating a straight-line trade-off region between the two goals (Muangkhiew, 2022).

The two main objectives in this study are:

- Minimizing TVD (Total Voltage Deviation)
- Minimizing TSoC (Total State of Charge deviation)

The FMOO-based PSO helps find the best balance between these two competing objectives. It is searching for the most suitable solution that offers a good trade-off between reducing TVD and TSoC.

Based on the objective functions in Eq. (5.6) and Eq. (5.7), membership functions are created, as shown in Fig. (5.2) and Fig. (5.3). These functions help measure how well each solution meets the objectives. The functions can be expressed as follows:

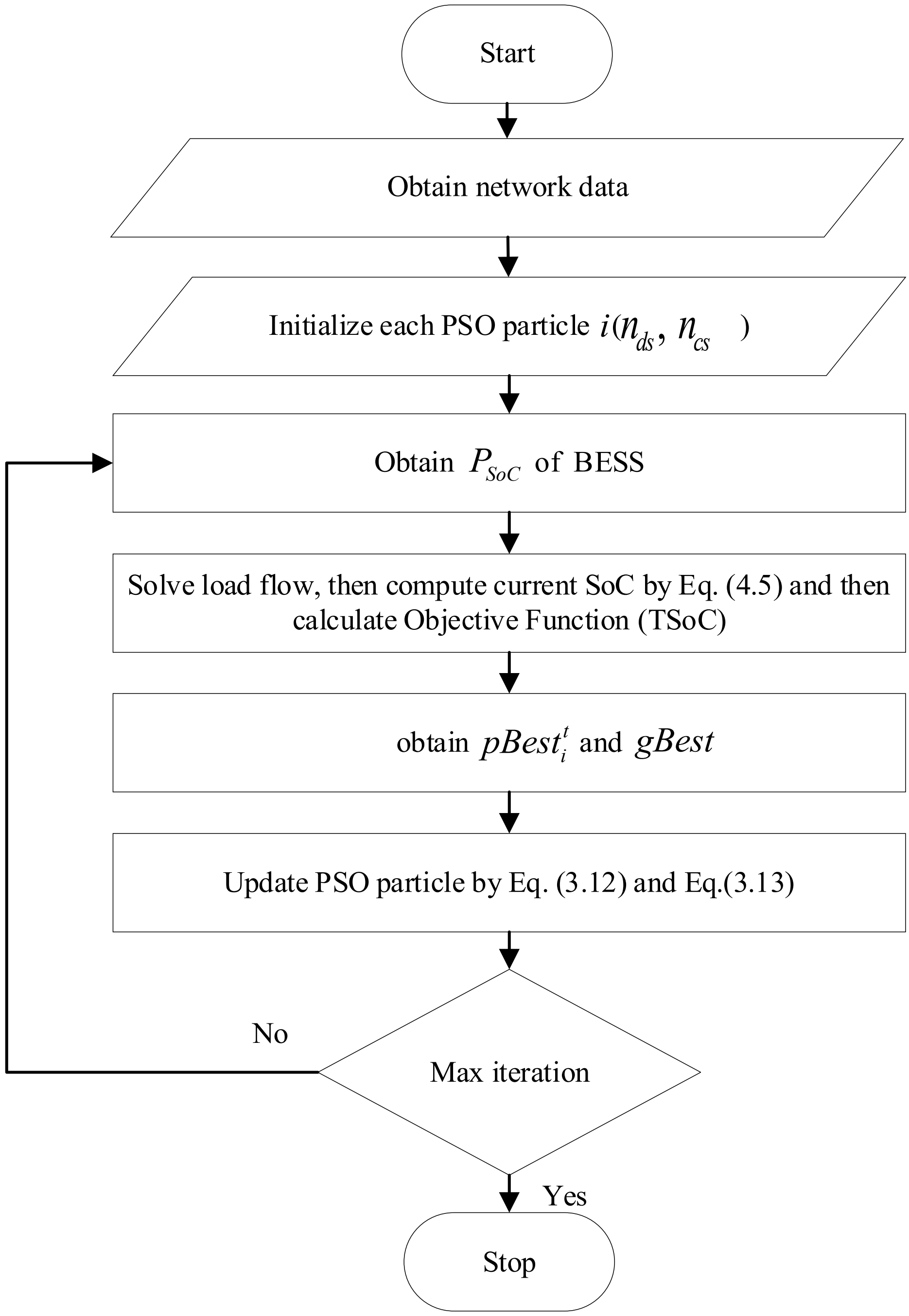

Figure 5.1 The PSO based BESS optimal TSoC computation procedure

membership function for Eq. (5.6)

$$\mu_{TSoC}(x)=\begin{cases}1, & \text{if } TSoC(x)\le TSoC_{\min}\\ \dfrac{TSoC_{\max}-TSoC(x)}{TSoC_{\max}-TSoC_{\min}}, & \text{if } TSoC_{\min}<TSoC(x)\le TSoC_{\max}\\ 0 & \text{if } TSoC(x)\ge TSoC_{\max}\end{cases} \tag{5.8}$$

membership function for Eq. (5.7)

$$\mu_{TVD}(x)=\begin{cases}1, & \text{if } TVD(x)\le TVD_{\min}\\ \dfrac{TVD_{\max}-TVD(x)}{TVD_{\max}-TVD_{\min}}, & \text{if } TVD_{\min}<TVD(x)\le TVD_{\max}\\ 0 & \text{if } TVD(x)\ge TVD_{\max}\end{cases} \tag{5.9}$$

The optimum fuzzy function can be obtained as follows:

$$\text{Maximize } \mu_T = \min\{\mu_{TSoC}(x), \mu_{TVD}(x)\} \tag{5.10}$$

The proposed computational procedure for the FMOO-based PSO is illustrated in Fig. 5.4.

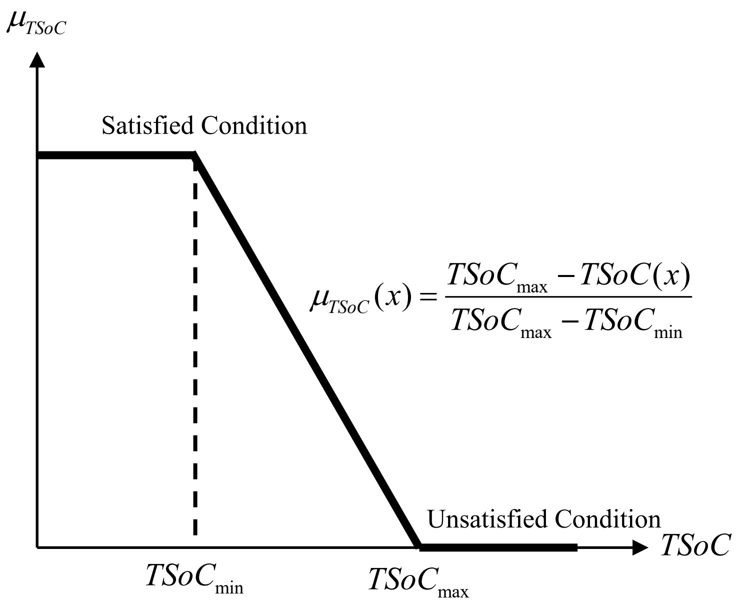

Figure 5.2 The Fuzzy membership function of total SoC deviation

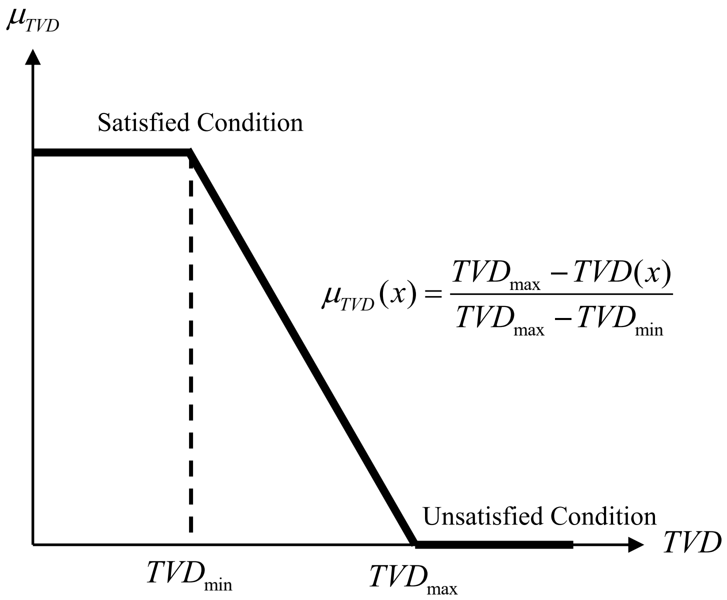

Figure 5.3 The Fuzzy membership function of total voltage deviation

5.5 PSO Parameter Selection and Tuning

For the PSO process, it is essential to carefully tune several key parameters to ensure optimal performance. These parameters include the self-adjustment weight, social-adjustment weight, inertia weight range, maximum number of iterations, and the size of the swarm. Each of these factors plays a significant role in determining both the quality of the solution and the computational efficiency of the optimization process. To systematically investigate the effects of these parameters, we conducted a comprehensive full factorial exploration, as detailed in Table 5.1. This exploration covered a total of 1,176 different parameter combinations, allowing us to thoroughly assess the impact of each setting. The results of this extensive study are summarized and presented in Figure 5.5 and Table 5.2, providing valuable insights into the parameter configurations that yield the best performance.

In the proposed method, a battery is integrated into the system, and PSO is utilized with the specific objective of minimizing the total voltage deviation . Through numerous trial runs and iterative adjustments, the PSO parameters were ultimately set as follows: the inertia weight was varied within the range of 0.3 to 0.7,

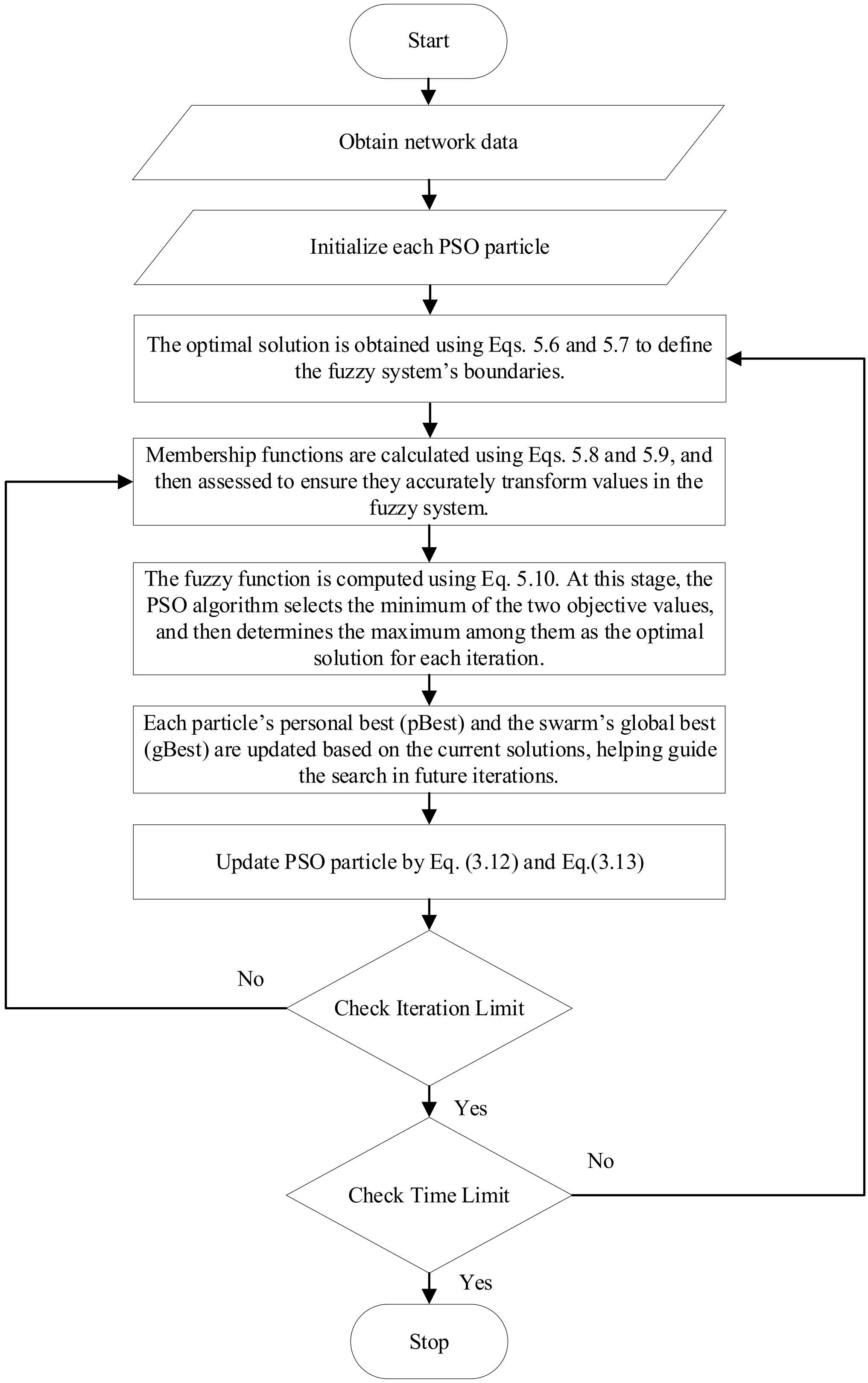

Figure 5.4 The FMOO-based PSO computation procedure

while both the self-adjustment weight and the social-adjustment weight were assigned values of 1 and 2, respectively. Additionally, the maximum number of iterations was fixed at 100, and the swarm size was also set to 100.

In addition, the minimization of the total SoC deviation was also considered. For this objective, the inertia weight was varied within the range of 0.1 to 1.1, while the self-adjustment weight and the social-adjustment weight were set to 1 and 2, respectively. This configuration resulted in an optimal objective function value of 0.90023, with a computation time of 20 seconds, as illustrated in Figure 5.6 and table 5.3.

For the Fuzzy Multi-objective approach, the inertia weight varied from 0.1 to 0.9, and both the self-adjustment weight and the social-adjustment weight were set to 2. This setup yielded an optimal objective function value of 0.8924, with a computation time of 30 seconds, as shown in Figure 5.7 and table 5.4.

These parameter values were selected based on their consistent ability to deliver optimal results across multiple experimental runs. With this carefully chosen configuration, the PSO algorithm was able to achieve the best possible outcome for the given objective function, effectively minimizing the total voltage deviation within the system.

Table 5.1 PSO Parameter Ranges for Testing

Parameter	Symbols	Values in Test Set
Self-Adjustment Weight	c_1	[1.1, 1.0, 0.9, 0.8, 0.7, 0.6]
Social Adjustment Weight	c_2	[0.1, 0.2, 0.3, 0.4]
Inertia Range	w	[1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0]

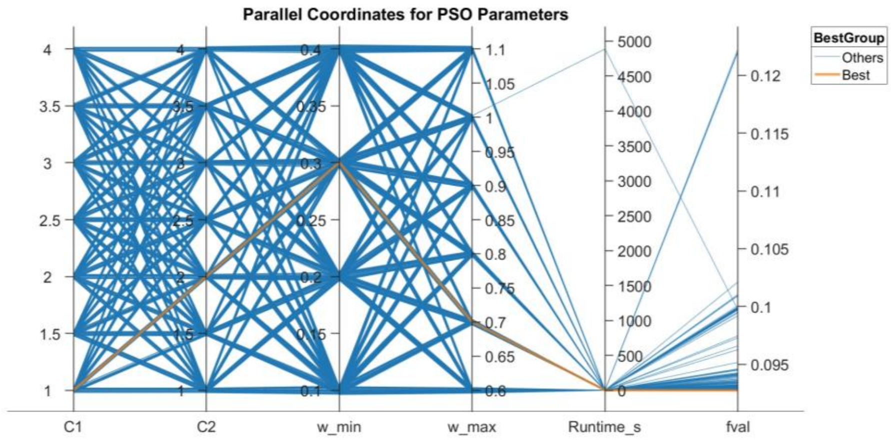

Figure 5.5 PSO parameter for TVD objective

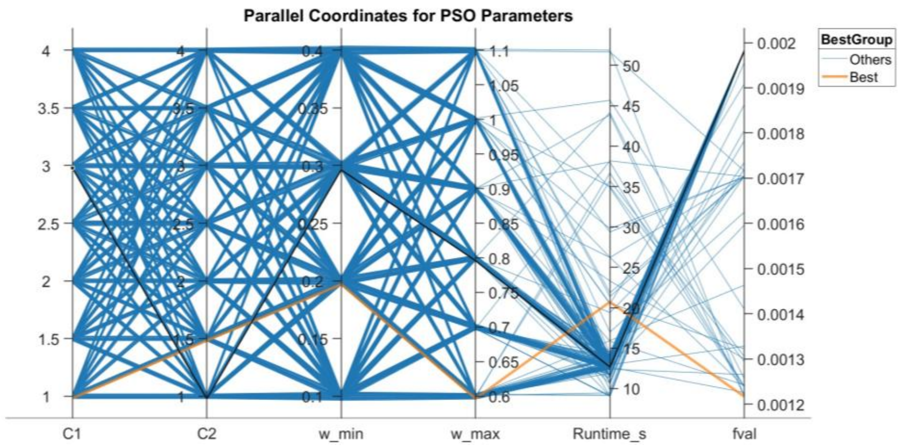

Figure 5.6 PSO parameter for TSoC objective

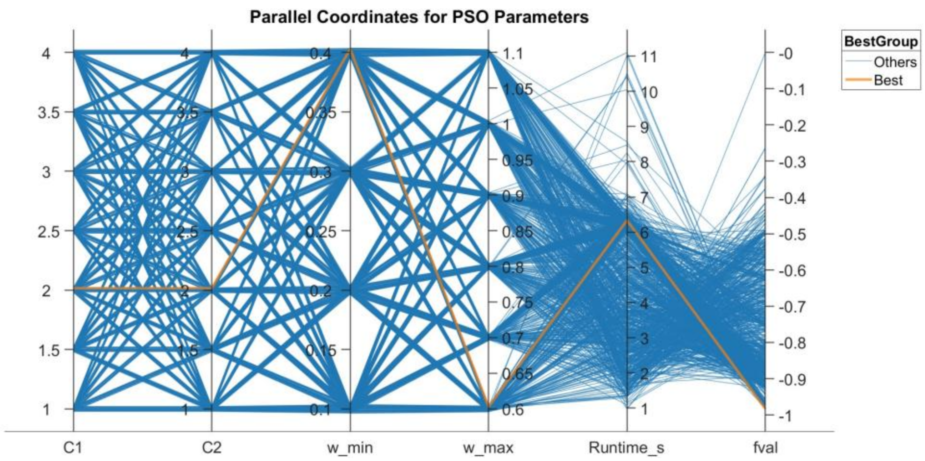

Figure 5.7 PSO parameter for Fuzzy Multi-objective

Table 5.2 PSO Parameter for TVD objective

Parameter	Symbols	Settings
Self-Adjustment Weight	c_1	1
Social Adjustment Weight	c_2	2
Max Inertia Range	w_{max}	0.7
Min Inertia Range	w_{min}	0.3
Max Iteration	-	100
Swarm Size	-	100

Table 5.3 PSO Parameter for TSoC objective

Parameter	Symbols	Settings
Self-Adjustment Weight	c_1	1
Social Adjustment Weight	c_2	1.5
Max Inertia Range	w_{max}	0.6
Min Inertia Range	w_{min}	0.2
Max Iteration	-	100
Swarm Size	-	100

Table 5.4 PSO Parameter for Fuzzy Multi-objective

Parameter	Symbols	Settings
Self-Adjustment Weight	c_1	2
Social Adjustment Weight	c_2	2
Max Inertia Range	w_{max}	0.6
Min Inertia Range	w_{min}	0.4
Max Iteration	-	100
Swarm Size	-	100

5.6 Results and Discussion

The operation will be tested using the IEEE 33-bus and IEEE 69-bus distribution system, where scenarios of voltage rise, and voltage drop will be simulated to observe the performance of the proposed method. Furthermore, the tests are divided into 2 comparative cases as follows:

• case 5.5.3.1 modified IEEE 33-bus with PV and wind power penetration and BESS considering SoC restoration results

• case 5.5.3.2: modified IEEE 69-bus with PV and wind power penetration and BESS considering SoC restoration results

5.6.1 modified IEEE 33-bus with PV and wind power penetration and BESS considering SoC restoration results

In this case six scenarios considered, in which RE sources with a total capacity of 1.25 MW and BESS were installed at bus 18, 1.75 MW at bus 22, 3.5 MW at bus 25, and 3.5 MW at bus 33. The scenarios are as follows:

- Scenario 1 Wind power only: 1.25 MW wind, no PV installed
- Scenario 2 0.25 MW PV and 1.00 MW wind
- Scenario 3 0.50 MW PV and 0.75 MW wind
- Scenario 4 0.75 MW PV and 0.50 MW wind
- Scenario 5 1.00 MW PV and 0.25 MW wind
- Scenario 6 PV only: 1.25 MW PV, no wind installed

5.6.1.1 Scenario 1 Wind power only: 1.25 MW wind, no PV installed

In this study, the IEEE 33-bus distribution system was modeled with the integration of four 1.25 MW wind turbines installed at buses 18, 22, 25, and 33. Notably, no PV generation was included in this scenario, allowing for a focused assessment of the impact of wind power alone. Each wind turbine site was equipped with a BESS, which was managed by a FMOO-based PSO controller. The controller was designed to optimize the “adjust-exponent” parameter, as detailed in Table 5.5, in order to balance two key objectives: minimizing TVD across the network and maintaining the TSoC among the BESS units within acceptable limits.

Figure 5.9 illustrates the operational profile of the BESS at bus 18 over a 24-hour period. Due to the variable nature of wind generation, the power supplied to the grid fluctuates throughout the day, occasionally leading to over-voltage conditions, particularly during hours 8–10 and at hour 18. Figure 5.8 provides a detailed BESS Operation at a single time point to illustrate this multi-objective control. The process begins with the bus voltage at a high of 1.0278 p.u. At this moment, the FMOO based PSO controller determines a net power action by balancing two simultaneous objectives. As shown in the middle plot, the primary objective of voltage control requires a significant charge action (-0.2834 p.u.), while the secondary objective of restoring the SoC towards its 0.5 reference (from an initial 55.03%) calls for a discharge action (0.1277 p.u.).

The controller synthesizes these conflicting requirements into a single net charging action. This resulting net action effectively reduces the bus voltage to its final value of 1.0158 p.u., as shown in the "After Control" bar. The impact on the State of Charge, detailed in the right-hand plot, reflects this combined action. While the charging component for voltage control alone would raise the SoC to 61.70%, the actual net operation results in a final SoC of 58.70%. This demonstrates the controller's ability to successfully mitigate the over-voltage condition while simultaneously managing the battery's state of charge, ensuring it remains prepared for future grid events.

The effectiveness of the FMOO based PSO approach is further demonstrated in Figures 5.10 and 5.11. For example, at hour 15, the maximum and minimum TVD values obtained from single-objective optimizations are 0.4939 p.u. and 0.3023 p.u., respectively. The FMOO solution achieves a TVD of 0.3686 p.u., which lies between these extremes. Similarly, for the TSoC metric, the maximum and minimum values are 0.2353 and 0.0029, while the fuzzy solution yields 0.0832. These results indicate that the controller successfully balances the trade-off between voltage regulation and battery state-of-charge management, avoiding excessive deviation in either objective.

Overall, the findings confirm that the proposed FMOO based PSO controller enables robust voltage regulation and effective energy management in a wind-only scenario. By maintaining the BESS state of charge near the midpoint, the system ensures that storage resources are consistently available, contributing to the stability of the distribution network. This approach demonstrates the potential for integrating renewable energy sources with advanced control strategies to enhance the performance of modern power systems.

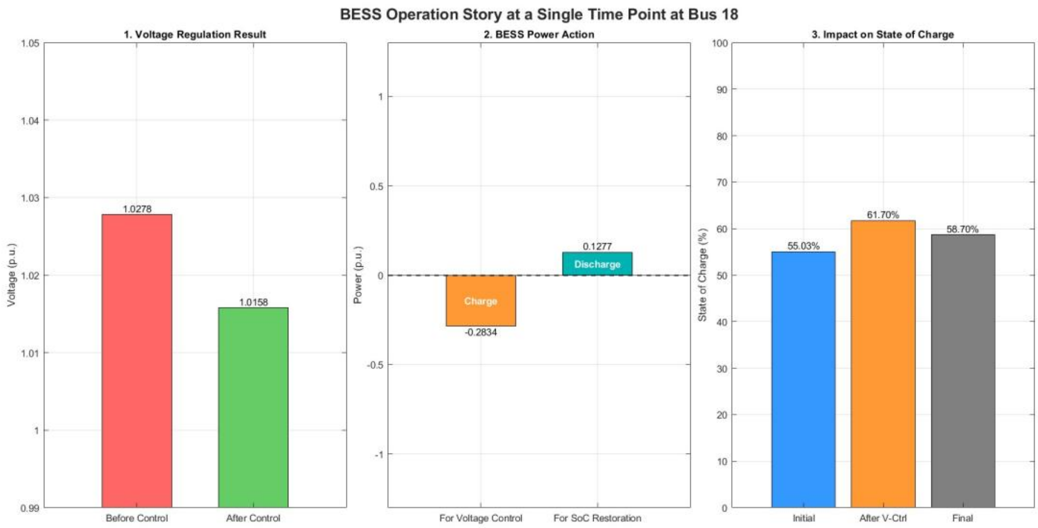

Figure 5.8 Overview of BESS Operation for Voltage Support scenario 1

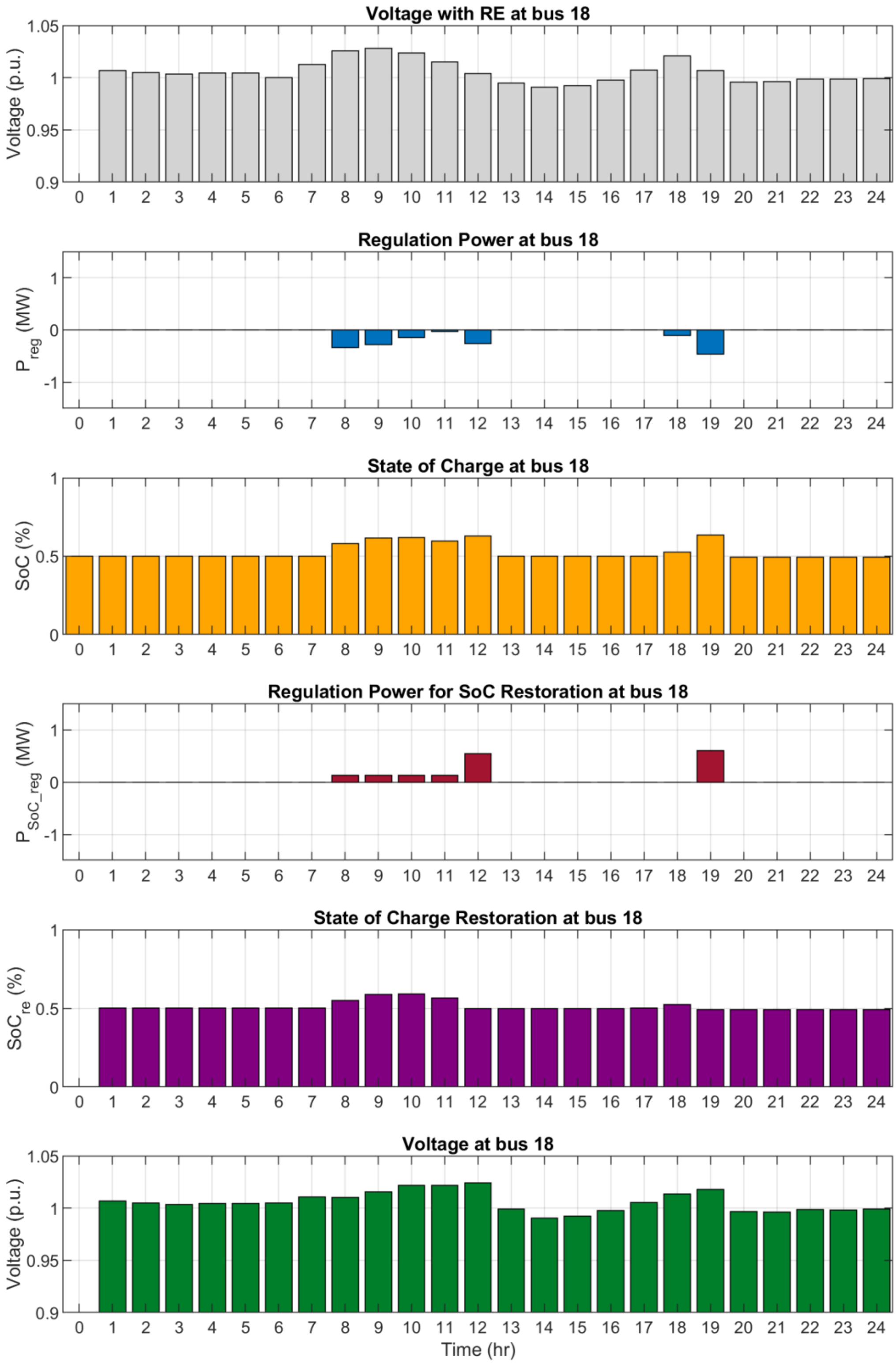

Figure 5.9 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 18 Scenario 1

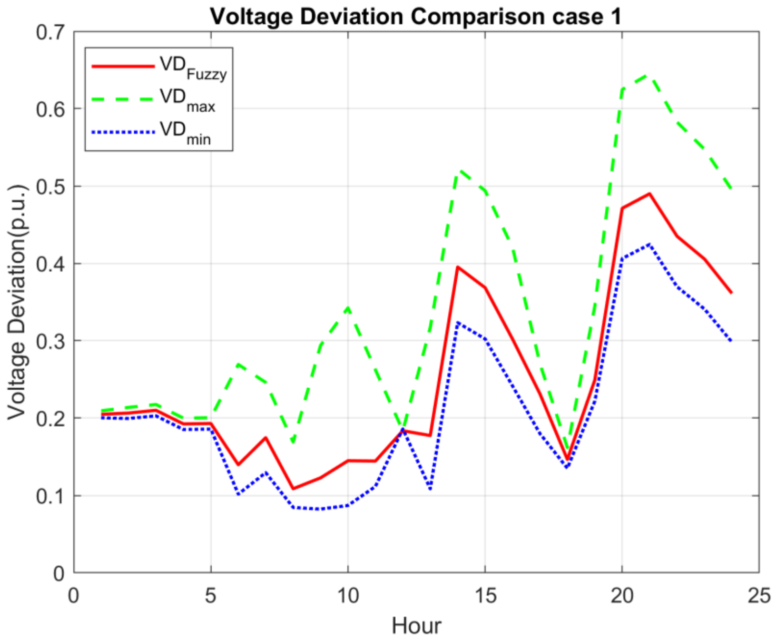

Figure 5.10 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective Voltage Deviation scenario 1

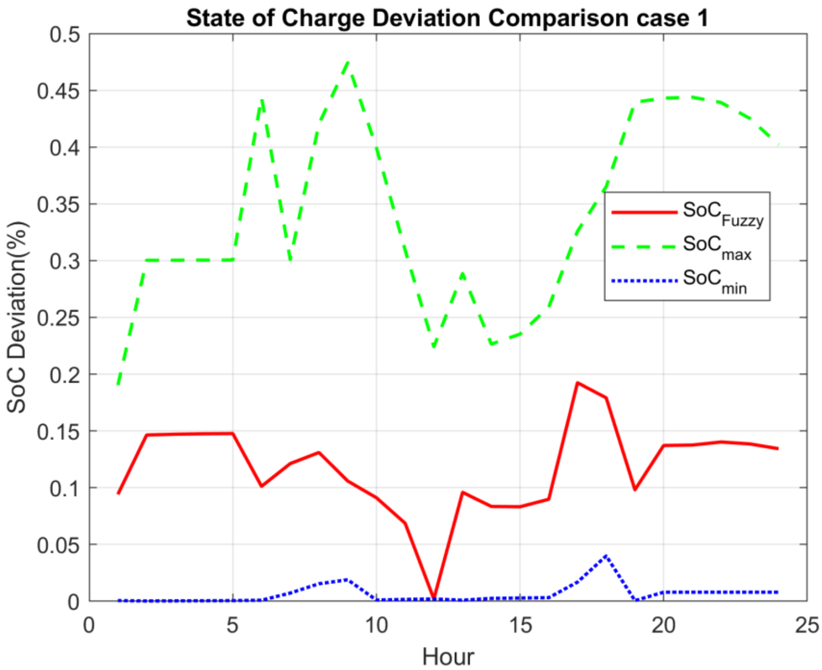

Figure 5.11 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective SoC Deviation scenario 1

Table 5.5 Optimal adjust-exponent values obtained with the fuzzy multi-objective PSO algorithm scenario 1

Hour	Control	Bus	n	Power (MW)	SoC
8	Voltage Deviation	18	16.2303	-0.3373	0.5803
		22	12.1134	-0.0828	0.6034
		25	0.1000	-0.0005	0.5002
		33	18.8230	-0.0498	0.4500
	SoC Deviation	18	0.1000	0.1272	0.5503
		22	0.1000	0.1275	0.5305
		25	3.4116	0.0000	0.5002
		33	0.1000	0.0000	0.4500
9	Voltage Deviation	18	13.1980	-0.2834	0.6170
		22	12.5637	-0.0737	0.5727
		25	0.1000	-0.0006	0.5003
		33	20.0000	-0.1098	0.4814
	SoC Deviation	18	0.1000	0.1277	0.5870
		22	0.1000	0.1271	0.5000
		25	8.1443	0.0000	0.5003
		33	17.1891	0.0000	0.4814
18	Voltage Deviation	18	13.1198	-0.1071	0.5254
		22	19.9961	-0.2595	0.8000
		25	0.1000	-0.0003	0.5006
		33	0.1000	-0.0000	0.4600
	SoC Deviation	18	0.1000	0.0000	0.5254
		22	3.9865	0.3270	0.6131
		25	4.4869	0.0000	0.5006
		33	0.1000	0.0000	0.4600

5.6.1.2 Scenario 2 0.25 MW PV and 1.00 MW wind

By adding a small photovoltaic (PV) system just 0.25 MW per site alongside the existing 1.00 MW wind turbines, the overall renewable generation profile now shows two distinct peaks. The first is a PV-driven rise between 9:00 AM and 3:00 PM, while the second, a wind-dominated peak, occurs in the early evening around 7:00 to 8:00 PM. At bus 18, these peaks push the voltage up to about 1.0255 p.u.

During peak generation periods, the BESS is set to charge, helping to pull the voltage back within acceptable limits, ensuring the voltage stays close to its nominal value throughout the entire 24-hour period, as illustrated in Figure 5.12. However, the controller is equally effective during times of low generation. To illustrate the controller's versatility, Figure 5.13 presents a BESS Operation during a moment of under-voltage at bus 18. At this specific time, the voltage has dropped to 0.9791 p.u. The FMOO PSO controller determines a net power action by balancing two conflicting objectives. The primary response to correct the under-voltage is to discharge power into the grid (0.9531 p.u.). Simultaneously, with the initial SoC slightly high at 51.99%, the secondary objective of SoC restoration calls for a charging action (-0.4225 p.u.) to move it closer to the 50% target. The controller synthesizes these opposing needs into a net discharge command, which successfully raises the bus voltage to 1.0134 p.u. The impact of this balanced action on the SoC is shown in the right-hand plot while discharging for voltage control alone would have caused the SoC to plummet to 29.56%, the actual net operation results in a more moderate final SoC of 39.51%. At the most challenging time around 9:00 AM the single-objective optimization methods produce a maximum TVD of 0.1541 p.u. and a minimum of 0.0880 p.u., while the fuzzy logic controller lands somewhere in between at 0.1070 p.u. Similarly, the TSoC ranges from 0.0036 to 0.3842 across the single-objective runs, with the fuzzy controller achieving a more balanced result of 0.1129 as shown in Figures 5.14 and 5.15.

These results highlight how the algorithm tuned using PSO effectively balances performance by selecting an optimal n, detailed in Table 5.6. In summary, while the small addition of PV slightly increases the evening over-voltage, it has little effect on midday conditions. The proposed controller continues to manage voltage effectively throughout the day.

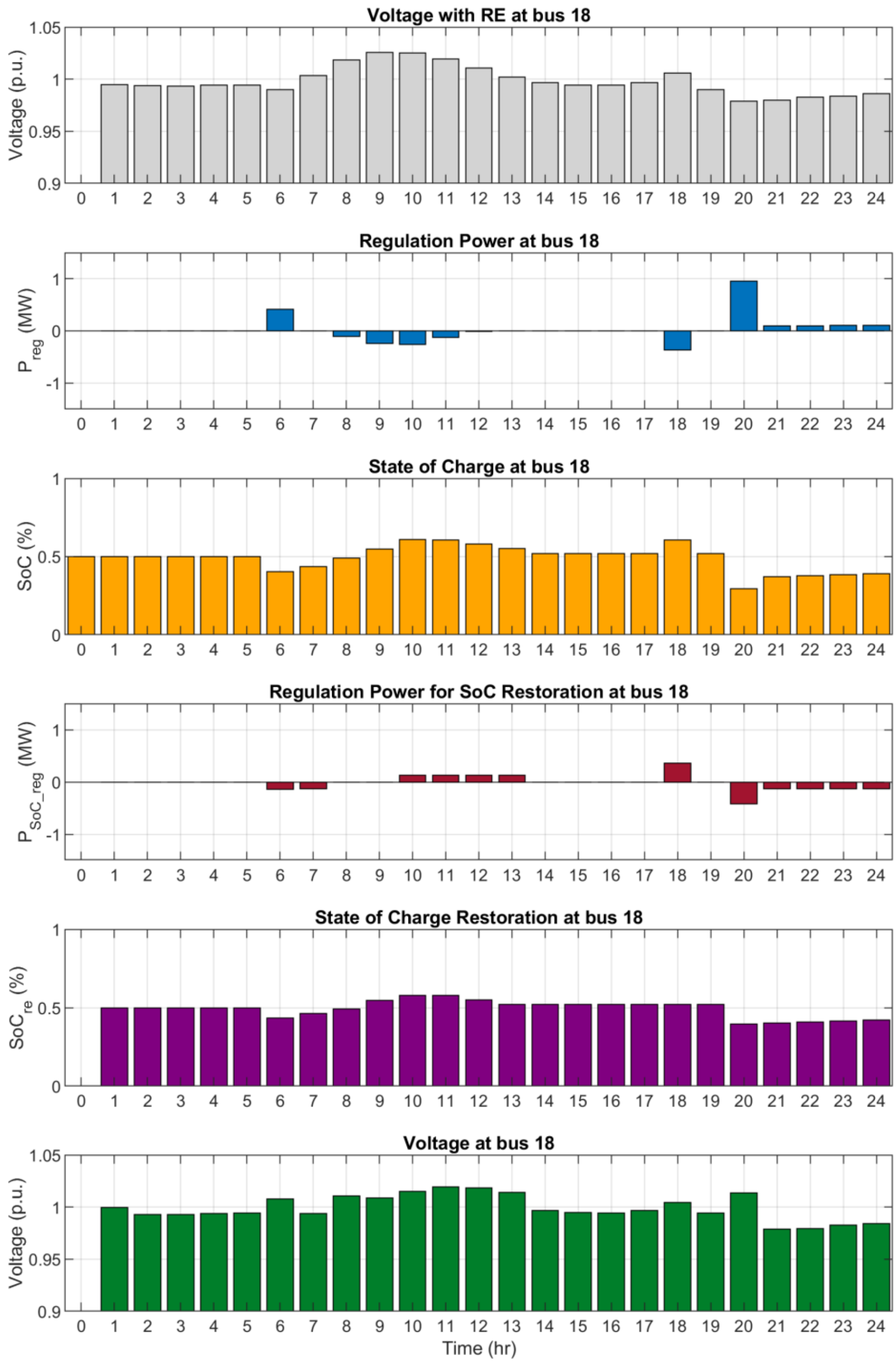

Figure 5.12 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 18 Scenario 2

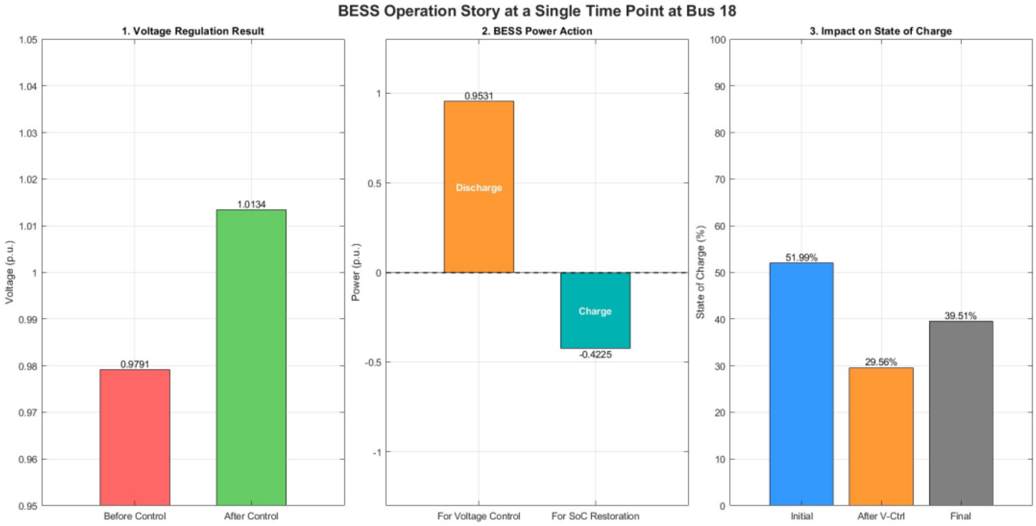

Figure 5.13 Overview of BESS Operation for Voltage Support scenario 2

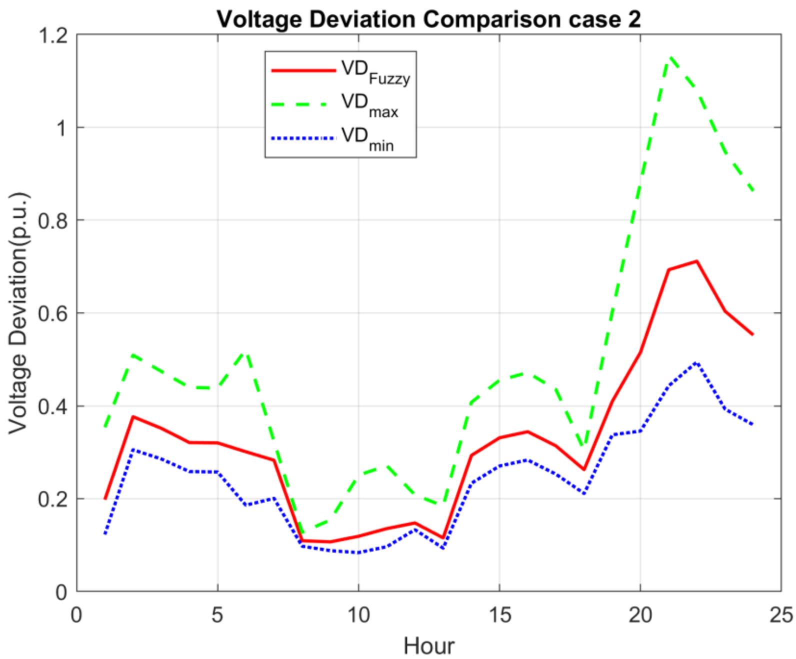

Figure 5.14 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective Voltage Deviation scenario 2

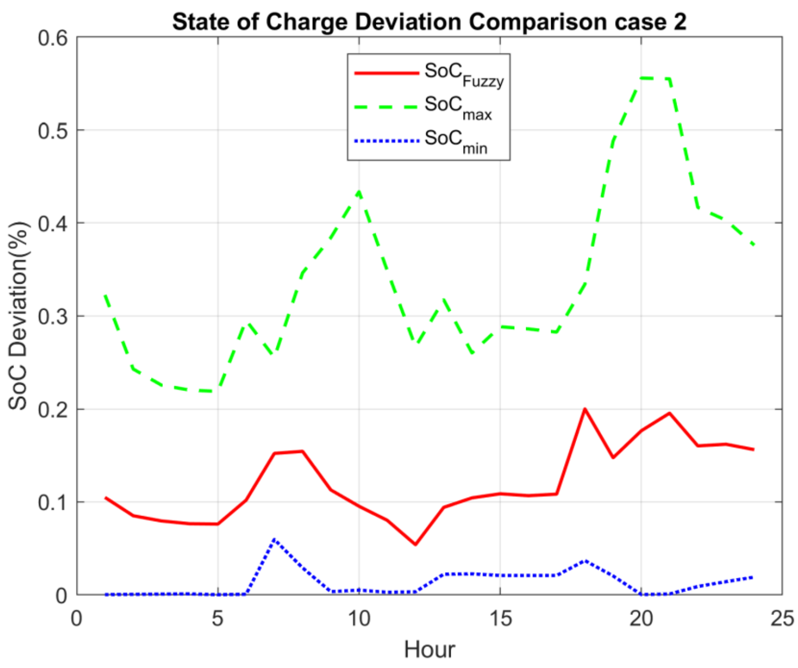

Figure 5.15 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective SoC Deviation scenario 2

Table 5.6 Optimal adjust-exponent values obtained with the fuzzy multi-objective PSO algorithm scenario 2

Hour	Control	Bus	n	Power (MW)	SoC
6	Voltage Deviation	18	20.0000	0.4132	0.4028
		22	0.1000	-0.0004	0.5005
		25	19.9967	0.0000	0.5000
		33	0.1000	0.0020	0.4235
	SoC Deviation	18	1.4877	-0.1358	0.4347
		22	0.1000	0.0000	0.5005
		25	0.1000	0.0000	0.5000
		33	4.1943	-0.1413	0.4639

Table 5.6 Optimal adjust-exponent values obtained with the fuzzy multi-objective PSO algorithm scenario 2 (Continued)

Hour	Control	Bus	n	Power (MW)	SoC
9	Voltage Deviation	18	15.6228	-0.2392	0.5471
		22	0.1000	-0.0012	0.6097
		25	0.1000	-0.0005	0.5002
		33	0.1000	-0.0006	0.4641
	SoC Deviation	18	0.1202	0.0000	0.5471
		22	1.6964	0.1399	0.5297
		25	20.0000	0.0000	0.5002
		33	0.1000	0.0000	0.4641
20	Voltage Deviation	18	19.1362	0.9531	0.2956
		22	0.1000	-0.0007	0.5004
		25	1.4836	0.0016	0.5000
		33	0.2062	0.0036	0.3718
	SoC Deviation	18	8.2757	-0.4225	0.3951
		22	0.1000	0.0000	0.5004
		25	19.4877	0.0000	0.5000
		33	6.0080	-0.1994	0.4287

5.6.1.3 Scenario 3 0.50 MW PV and 0.75 MW wind

From Figure 5.16, Increasing the PV rating to 0.50 MW shifts more of the generation to the middle of the day, creating a noticeable voltage hump between 9:00 and 11:00 AM. Although the evening wind peak is still present, it’s now less dominant. Over-voltage conditions first occur at hour 10, reaching a value of 1.0266 p.u. The BESS steps in to absorb this excess energy and later discharges in the late afternoon to bring its SoC back to the target level. The BESS Operation for this scenario at hour 10 is detailed in Figure 5.17. At this moment, the system faces a significant over-voltage of 1.0237 p.u. due to high solar generation. The controller's multi-objective logic weighs two powerful, conflicting actions: To correct the high voltage, a very strong charging action is required (-1.0313 p.u.). Conversely, to restore the already high initial SoC of 55.73% back towards the 50% target, a strong discharge action is needed (0.9226 p.u.).

The controller balances these opposing demands, resulting in a small net charging action. This nuanced response successfully lowers the voltage to 1.0153 p.u. while preventing severe overcharging of the battery. The right-hand plot starkly illustrates this trade-off: while the voltage control component alone would have driven the SoC to a critical level of 80.00%, the final, balanced action results in an actual SoC of just 58.29%.

Figures 5.18 and 5.19, along with Table 5.7, illustrate how the system operates under these new conditions using PSO. At hour 10, the TVD ranges from a maximum of 0.1258 p.u. to a minimum of 0.0861 p.u., while the fuzzy logic controller produces a well-balanced result of 0.1080 p.u. For SoC, the values span from 0.0213 to 0.3503 p.u., with the fuzzy controller again settling at 0.1093 p.u.

In short, increasing the solar share shifts the primary voltage regulation challenge to midday. However, the fuzzy PSO-based control scheme handles this transition smoothly, staying well within its operational limits.

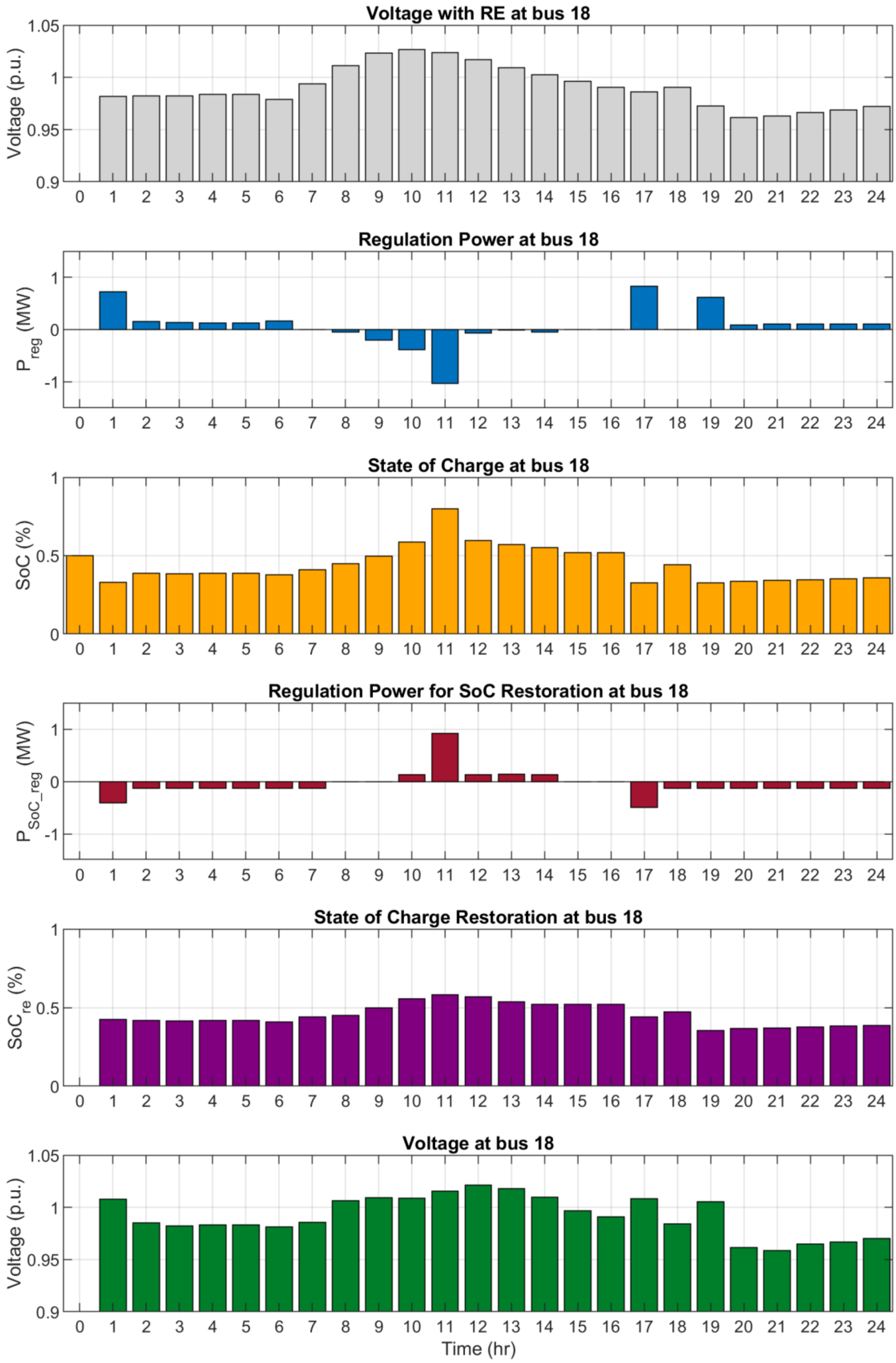

Figure 5.16 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 18 Scenario 3

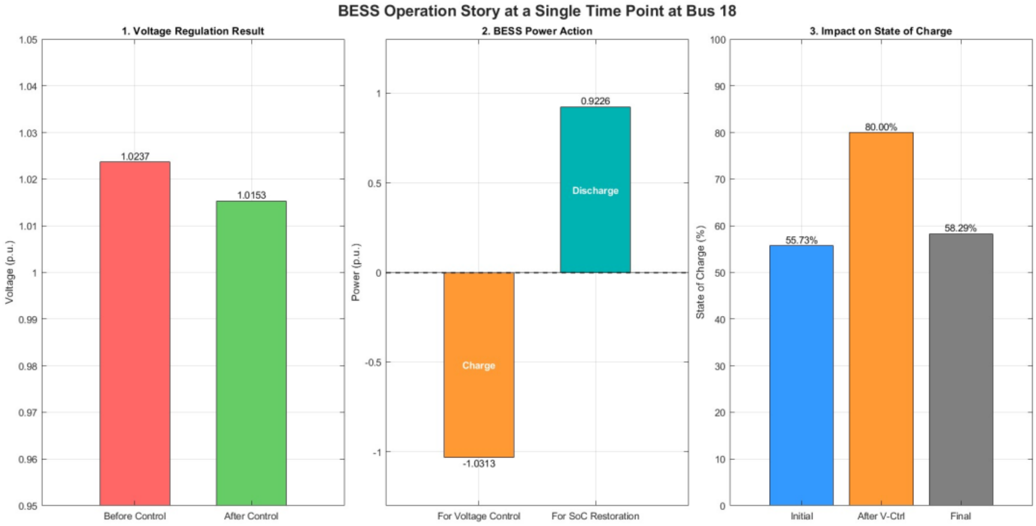

Figure 5.17 Overview of BESS Operation for Voltage Support scenario 3

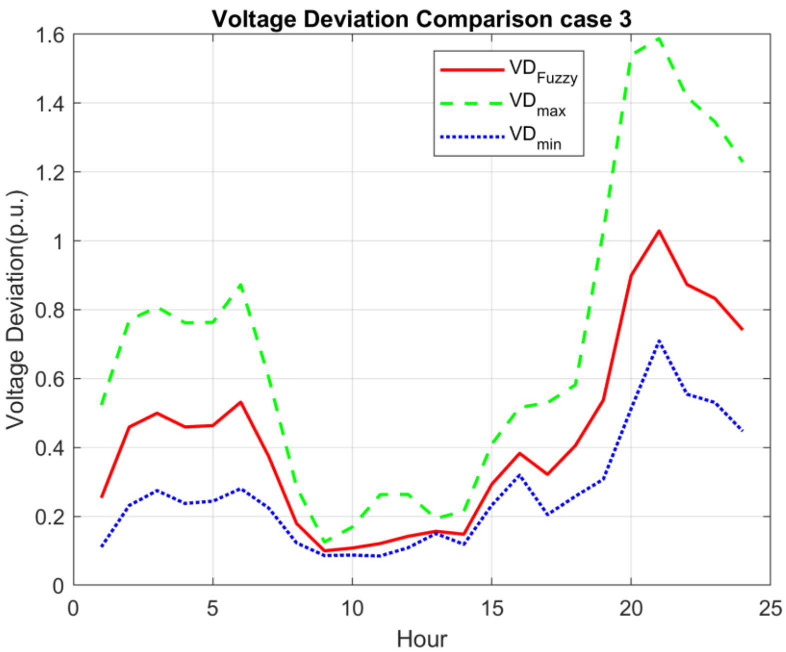

Figure 5.18 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective Voltage Deviation scenario 3

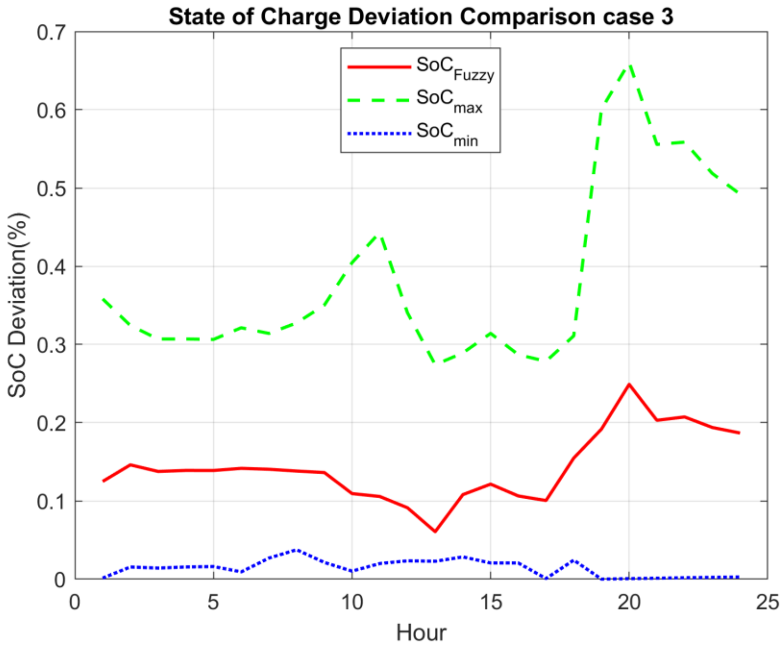

Figure 5.19 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective SoC Deviation scenario 3

Table 5.7 Optimal adjust-exponent values obtained with the fuzzy multi-objective PSO algorithm scenario 3

Hour	Control	Bus	n	Power (MW)	SoC
6	Voltage Deviation	18	20.0000	0.1614	0.3794
		22	0.1000	-0.0002	0.5008
		25	20.0000	0.0000	0.5000
		33	20.0000	0.3470	0.3454
	SoC Deviation	18	0.1000	-0.1277	0.4094
		22	18.2114	0.0000	0.5008
		25	0.1000	0.0000	0.5000
		33	10.6838	-0.3655	0.4498

Table 5.7 Optimal adjust-exponent values obtained with the fuzzy multi-objective PSO algorithm scenario 3 (Continued)

Hour	Control	Bus	n	Power (MW)	SoC
11	Voltage Deviation	18	18.6100	-1.0313	0.8000
		22	17.4886	-0.2413	0.6475
		25	0.1000	-0.0004	0.5004
		33	19.4789	-0.0690	0.4777
	SoC Deviation	18	8.7942	0.9226	0.5829
		22	7.6169	0.2582	0.5000
		25	0.1111	0.0000	0.5004
		33	12.4026	0.0000	0.4777
20	Voltage Deviation	18	20.0000	0.0864	0.3353
		22	0.1000	-0.0003	0.5002
		25	0.1000	0.0016	0.4995
		33	17.2260	0.3607	0.3496
	SoC Deviation	18	0.1000	-0.1283	0.3654
		22	20.0000	0.0000	0.5002
		25	0.1000	0.0000	0.4995
		33	0.1000	-0.1281	0.3862

5.6.1.4 Scenario 4 0.75 MW PV and 0.50 MW wind

From figure 5.20 and figure 5.21, When PV generation becomes dominant at 0.75 MW the feeder begins to experience sustained over-voltage for several hours, particularly between 9:00 AM and noon, with the voltage peaking around 1.0281 p.u. To manage this, the BESS is required to charge over a longer period, pushing its SoC closer to the upper limit. Later in the day, the system discharges to restore the SoC to its reference level.

Figures 5.22 and 5.23, along with Table 5.8, present the system's performance under these conditions, optimized using PSO. At the most critical time, hour 10, the TVD ranges from a maximum of 0.1289 p.u. to a minimum of 0.0859 p.u., while the fuzzy controller achieves a balanced value of 0.1019 p.u. The SoC varies between 0.0002 and 0.3734 p.u., with the fuzzy solution settling at 0.1388 p.u.

Even with the heavier PV loading, the controller effectively limits the voltage rise and ensures that no single battery becomes fully saturated, demonstrating the robustness of the fuzzy PSO-based approach.

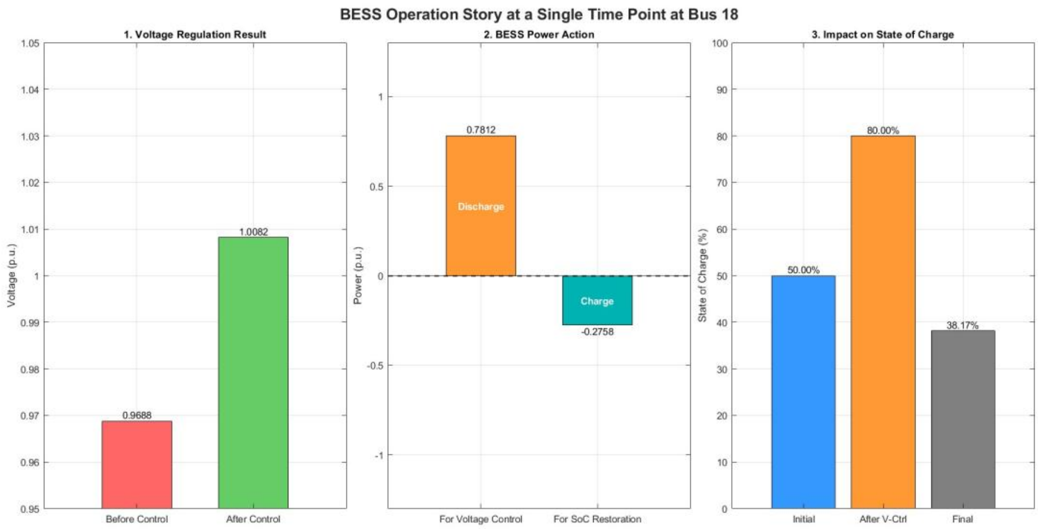

Figure 5.20 Overview of BESS Operation for Voltage Support Scenario 4

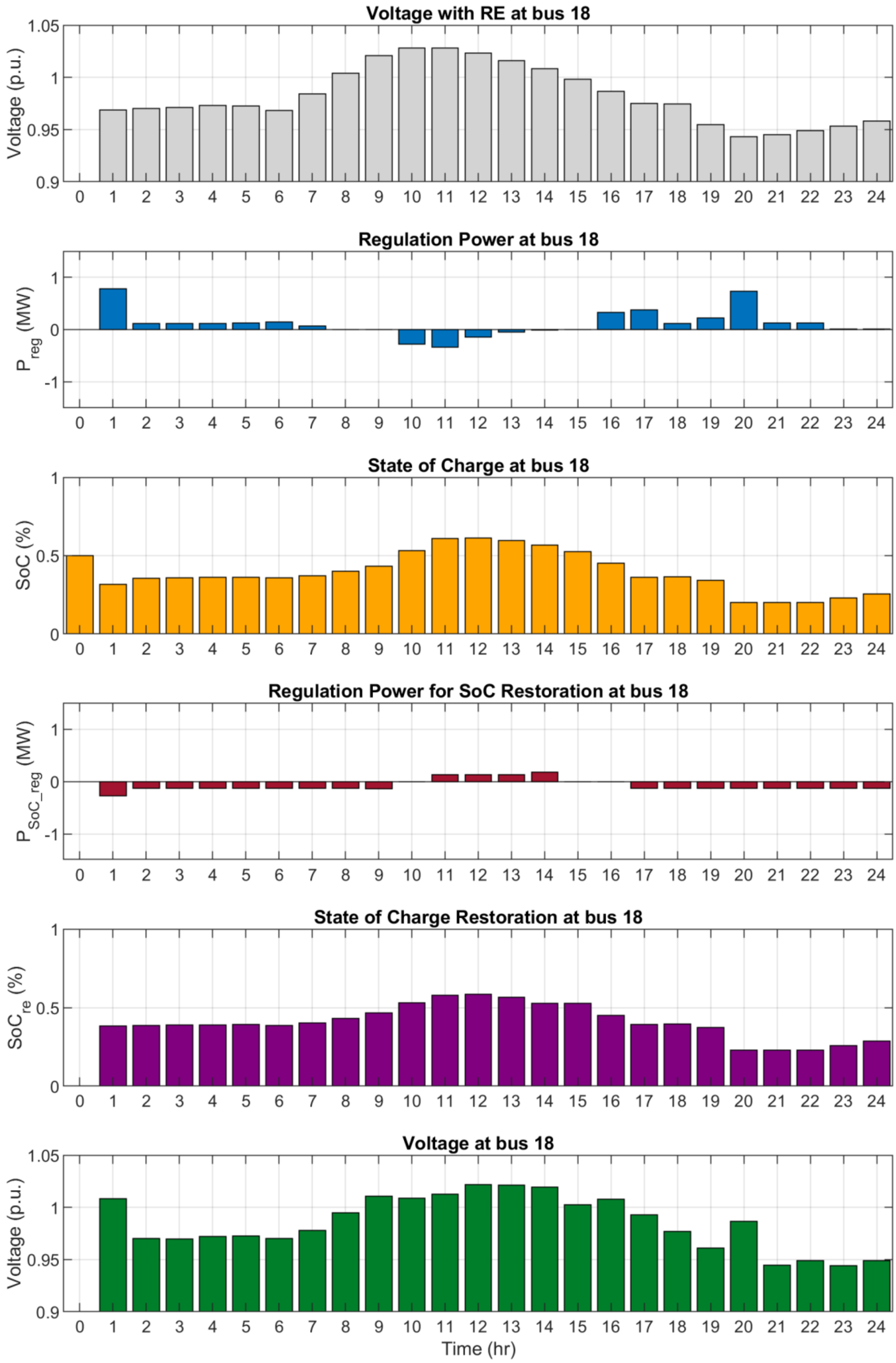

Figure 5.21 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 18 Scenario 4

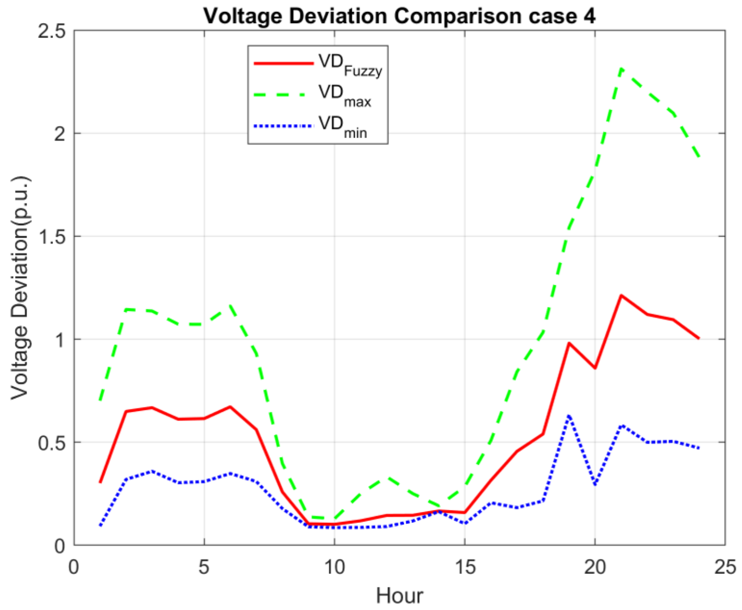

Figure 5.22 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective Voltage Deviation scenario 4

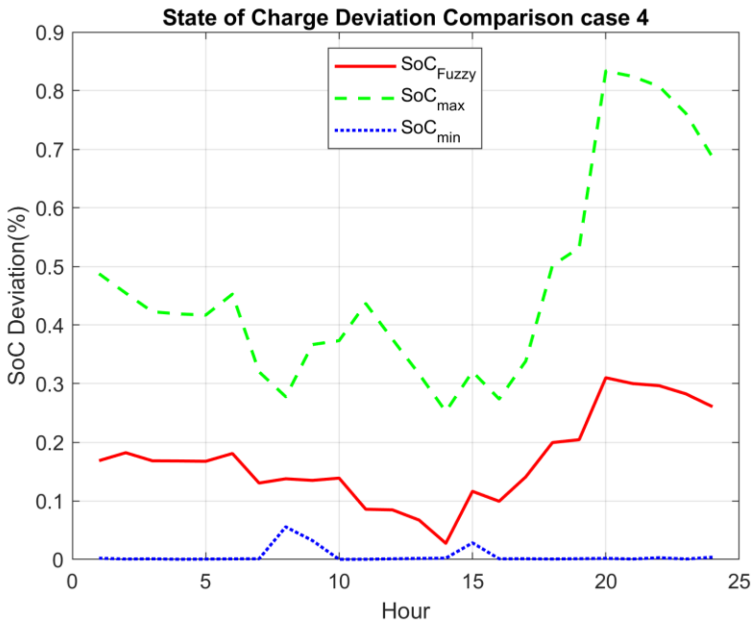

Figure 5.23 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective SoC Deviation scenario 4

Table 5.8 Optimal adjust-exponent values obtained with the fuzzy multi-objective PSO algorithm scenario 4

Hour	Control	Bus	n	Power (MW)	SoC
6	Voltage Deviation	18	20.0000	0.1473	0.3571
		22	0.1000	0.0000	0.5000
		25	0.1000	0.0012	0.4991
		33	15.9882	0.1572	0.3965
	SoC Deviation	18	0.1000	-0.1280	0.3872
		22	0.2599	0.0000	0.5000
		25	20.0000	0.0000	0.4991
		33	0.1000	-0.1275	0.4329
10	Voltage Deviation	18	17.2894	-0.2783	0.5312
		22	19.5058	-0.4024	0.8000
		25	0.1000	-0.0006	0.5002
		33	0.1000	-0.0008	0.4696
	SoC Deviation	18	0.1000	0.0000	0.5312
		22	4.7576	0.3902	0.5771
		25	20.0000	0.0000	0.5002
		33	1.9742	0.0000	0.4696
21	Voltage Deviation	18	4.0004	0.1300	0.2000
		22	7.3837	0.0000	0.5007
		25	0.1000	0.0020	0.4983
		33	14.8233	0.9138	0.2000
	SoC Deviation	18	0.1000	-0.1300	0.2306
		22	14.1961	0.0000	0.5007
		25	16.4983	0.0000	0.4983
		33	8.9480	-0.9507	0.4716

5.6.1.5 Scenario 5MW PV and 0.25 MW wind

From figure 5.24 and 5.25, With 1.00 MW of PV and only a small contribution from wind (0.25 MW), renewable generation becomes heavily concentrated around midday. As a result, the feeder voltage rises above 1.0 p.u. as early as 9:00 AM and peaks around 1.0321 p.u. near solar noon. Since wind generation in the evening is minimal, the BESS mainly discharges after 4:00 PM to bring its SoC back into balance.

Figures 5.26 to 5.27 and Table 5.9 present the system's behavior and optimization results using PSO. At hour 11, which is representative of peak solar input, the TVD ranges from a maximum of 0.1184 p.u. to a minimum of 0.0821 p.u., while the fuzzy controller achieves a more moderate value of 0.0965 p.u. The SoC varies from 0.0156 to 0.3721 p.u., with the fuzzy solution settling at 0.1575 p.u.

These results confirm that the BESS fleet can still handle a PV-dominated generation profile, though it comes at the cost of more intense cycling during midday hours.

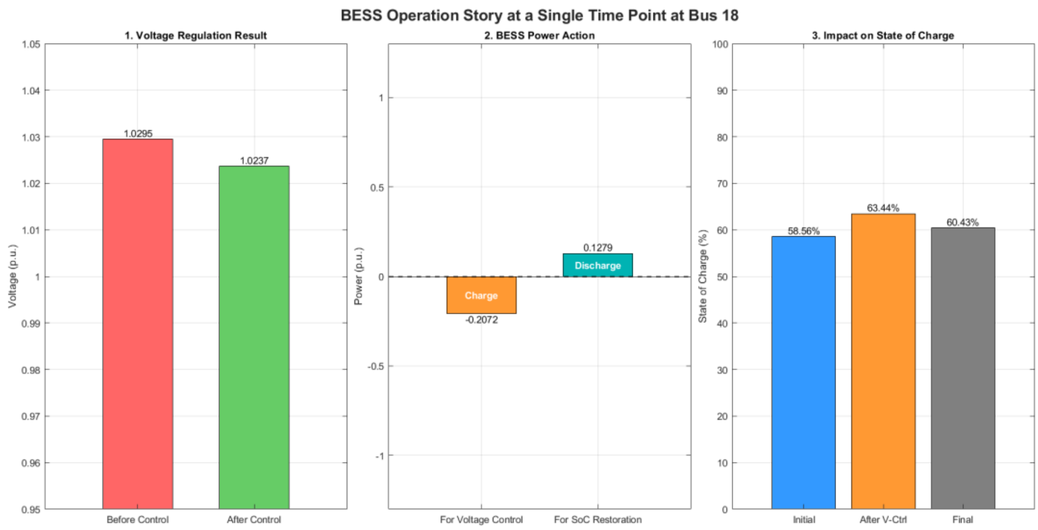

Figure 5.24 Overview of BESS Operation for Voltage Support Scenario 5

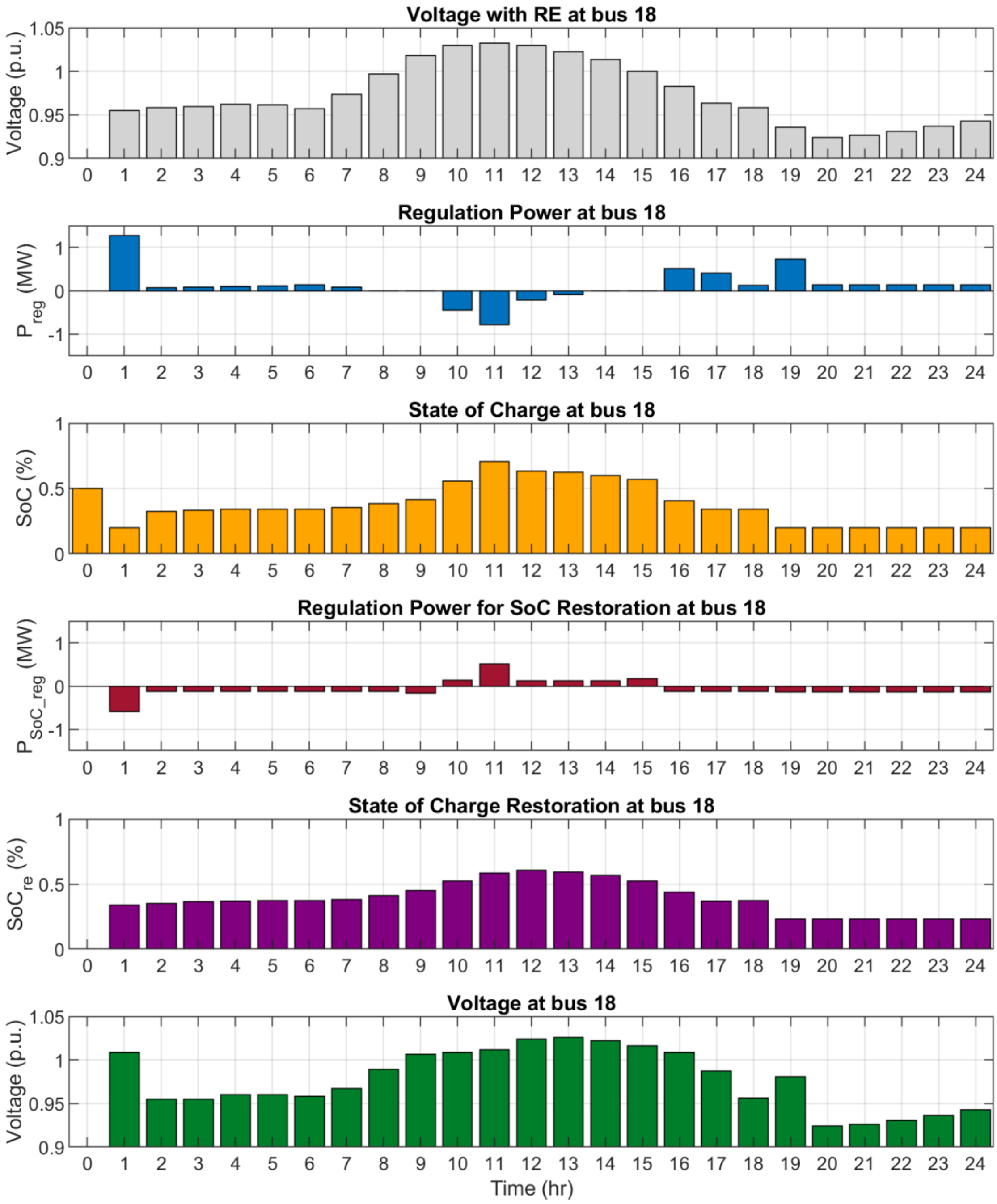

Figure 5.25 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 18 Scenario 5

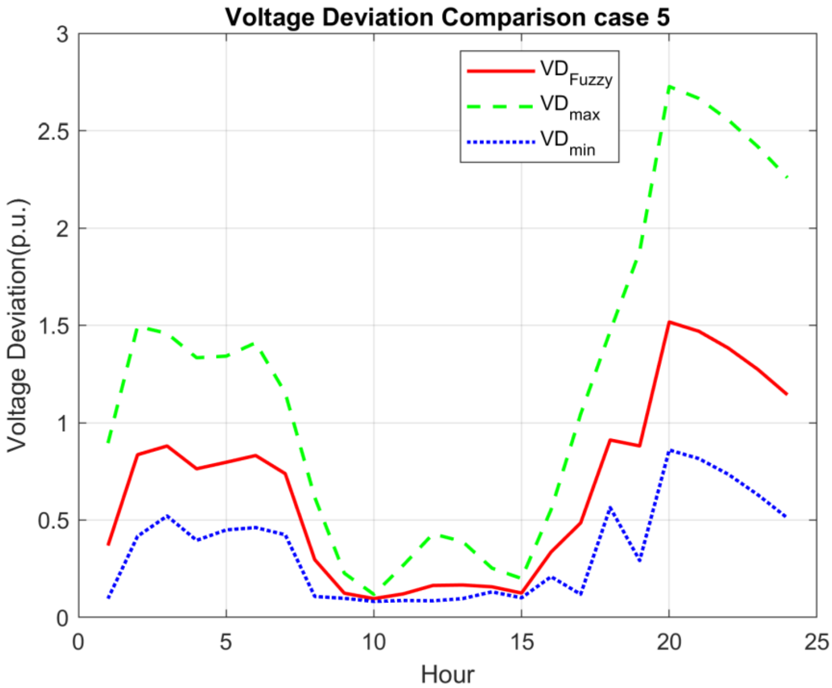

Figure 5.26 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective Voltage Deviation scenario 5

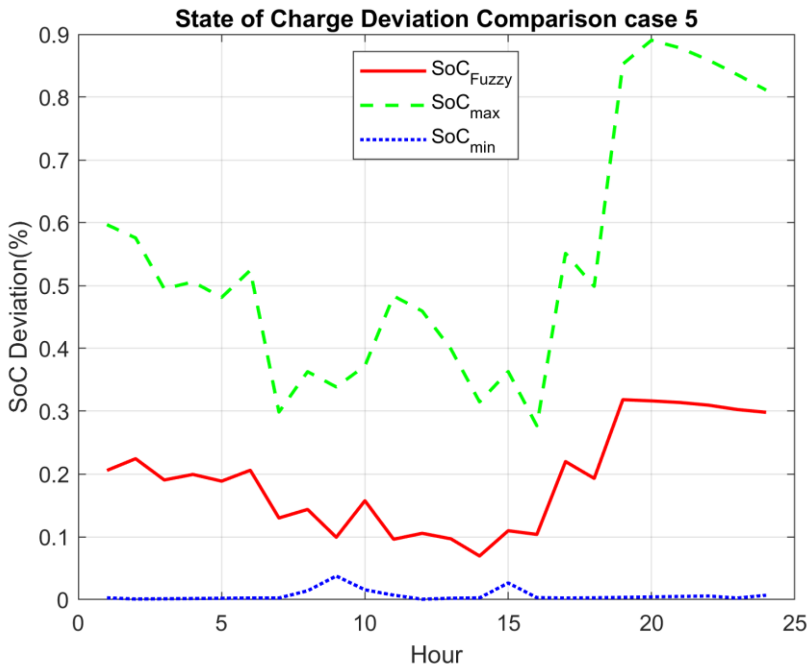

Figure 5.27 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective SoC Deviation scenario 5

Table 5.9 Optimal adjust-exponent values obtained with the fuzzy multi-objective PSO algorithm scenario 5

Hour	Control	Bus	n	Power (MW)	SoC
3	Voltage Deviation	18	20.0000	0.0849	0.3326
		22	0.1000	0.0000	0.5000
		25	0.1000	0.0014	0.4987
		33	10.8639	0.0430	0.4117
	SoC Deviation	18	0.1000	-0.1283	0.3628
		22	19.9287	0.0000	0.5000
		25	20.0000	0.0000	0.4987
		33	0.1000	-0.1273	0.4481
10	Voltage Deviation	18	19.8917	-0.4420	0.5556
		22	20.0000	-0.4937	0.7830
		25	0.1000	-0.0006	0.5002
		33	0.1000	-0.0009	0.4503
	SoC Deviation	18	20.0000	0.1414	0.5223
		22	4.5422	0.3461	0.5852
		25	0.1000	0.0000	0.5002
		33	19.6330	0.0000	0.4503
19	Voltage Deviation	18	20.0000	0.7256	0.2000
		22	4.9004	0.0000	0.5024
		25	0.1000	0.0023	0.4989
		33	0.1162	0.8371	0.2000
	SoC Deviation	18	0.1000	-0.1300	0.2306
		22	15.9159	0.0000	0.5024
		25	0.1206	0.0000	0.4989
		33	8.6168	-0.8910	0.4546

5.6.1.6 Scenario 6 PV only: 1.25 MW PV, no wind installed

From figure 5.28 and 5.29, In the PV-only scenario, the entire 1.25 MW of renewable output is concentrated during daylight hours, resulting in a single, broad over-voltage plateau between 9:00 AM and 2:00 PM, peaking at around 1.0363 p.u. During this period, all BESS units charge aggressively, driving their SoC close to the upper limit. A staged discharge follows in the late afternoon, gradually bringing each battery back to around 0.50 by sunset.

Figures 5.30 to 5.31 and Table 5.10 present the system's response under this condition, optimized using PSO. At peak hour 11 the TVD ranges from a maximum of 0.2729 p.u. to a minimum of 0.0816 p.u., with the fuzzy controller achieving a more balanced result of 0.1128 p.u. SoC values vary from 0.0033 to 0.4279 p.u., and the fuzzy solution settles at 0.0724 p.u.

Despite the intense midday stress, the fuzzy multi-objective PSO controller is able to maintain voltages within acceptable limits for most of the day. However, slight under-voltage is observed during hours 20 and 21, likely due to the limited BESS capacity being unable to support voltage at those late hours. Even so, the controller successfully prevents long-term SoC drift, highlighting the resilience of the control strategy even in a scenario powered entirely by solar energy.

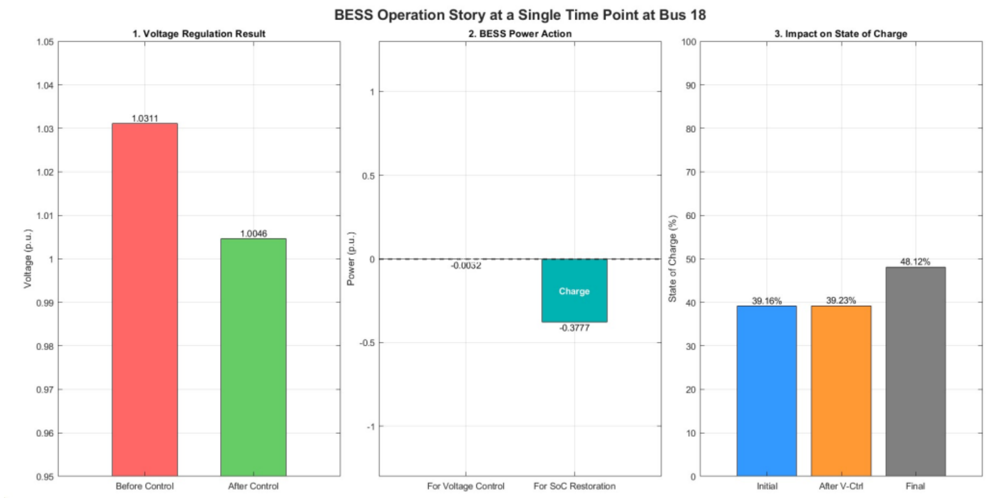

Figure 5.28 Overview of BESS Operation for Voltage Support Scenario 6

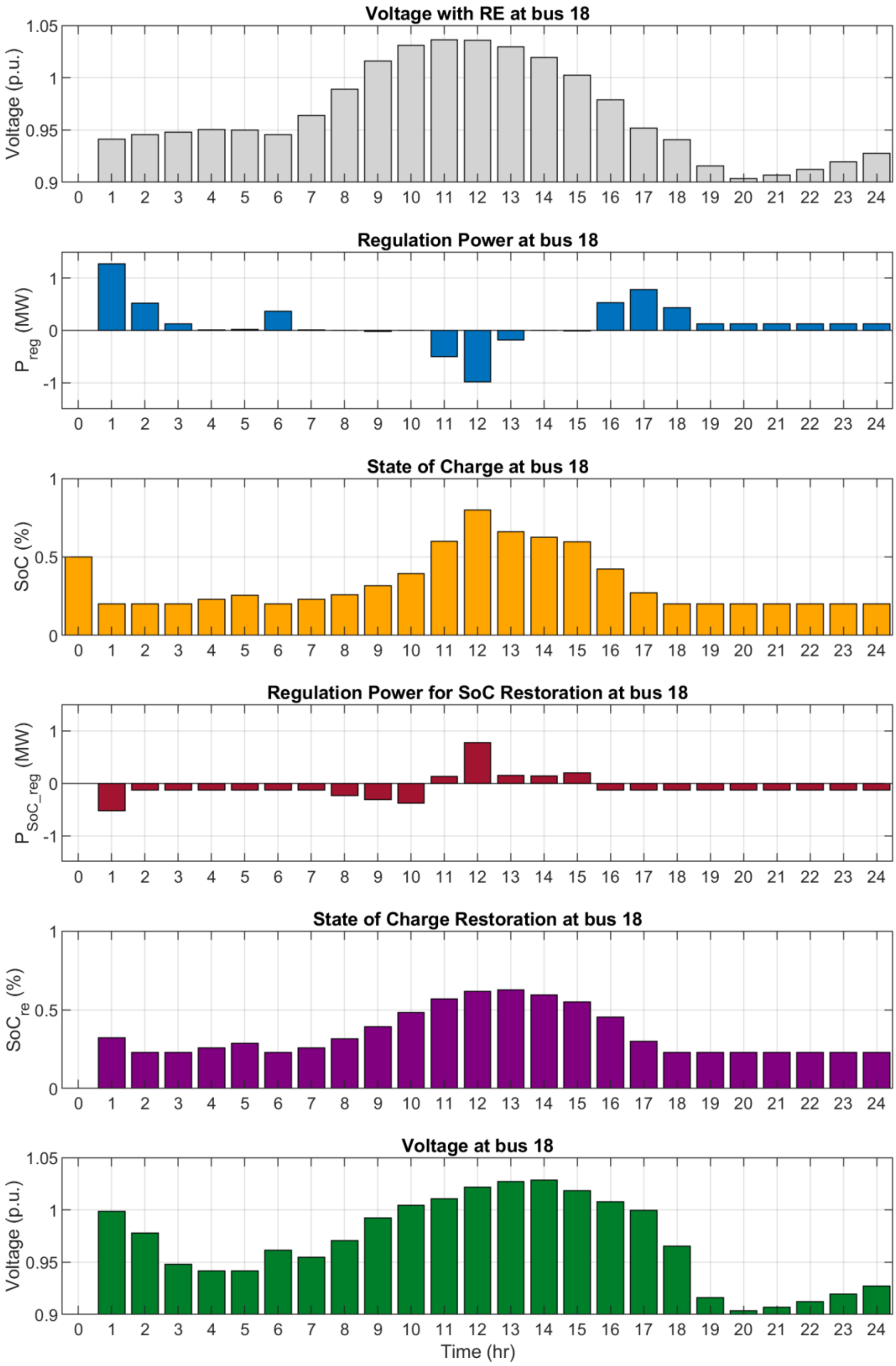

Figure 5.29 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 18 Scenario 6

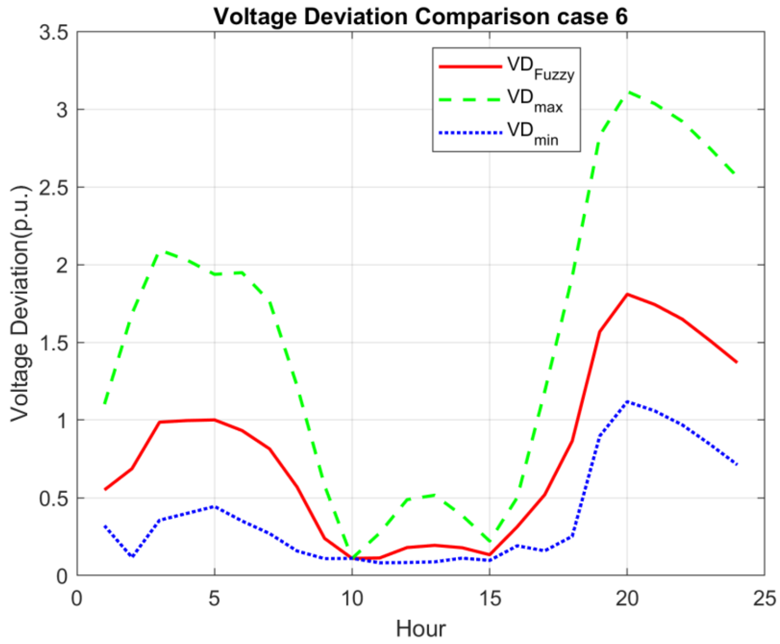

Figure 5.30 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective Voltage Deviation scenario 6

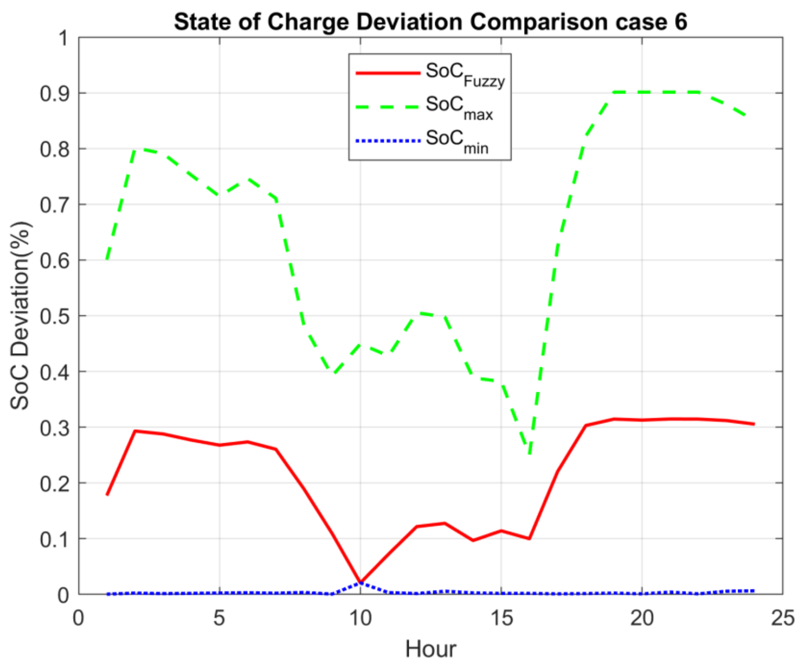

Figure 5.31 Comparison of Maximum, Minimum, and Fuzzy Multi-Objective SoC Deviation scenario 6

Table 5.10 Optimal adjust-exponent values obtained with the fuzzy multi-objective PSO algorithm scenario 6

Hour	Control	Bus	n	Power (MW)	SoC
3	Voltage Deviation	18	0.6991	0.1300	0.2000
		22	20.0000	0.0000	0.5000
		25	0.1000	0.0017	0.4984
		33	12.7077	0.1534	0.4335
	SoC Deviation	18	0.1000	-0.1300	0.2306
		22	18.1804	0.0000	0.5000
		25	0.1000	0.0000	0.4984
		33	19.6737	-0.1736	0.4831
10	Voltage Deviation	18	0.1000	-0.0032	0.3923
		22	0.1000	-0.0013	0.5014
		25	0.1000	-0.0007	0.5002
		33	0.1000	-0.0010	0.5003
	SoC Deviation	18	20.0000	-0.3777	0.4812
		22	2.4770	0.0000	0.5014
		25	19.9587	0.0000	0.5002
		33	0.1000	0.0000	0.5003
19	Voltage Deviation	18	20.0000	0.1300	0.2000
		22	0.4581	0.0000	0.5011
		25	0.1000	0.0028	0.4986
		33	13.4846	0.9379	0.2000
	SoC Deviation	18	0.1000	-0.1300	0.2306
		22	9.3085	0.0000	0.5011
		25	0.1000	0.0000	0.4986
		33	8.6705	-0.9005	0.4573

5.6.2 modified IEEE 69-bus with PV and wind power penetration and BESS considering SoC restoration results

In this case five scenarios considered, in which RE sources with a total capacity of 1.00 MW were installed at buses 27, 35, 46, 50, 52, 65, 67, and 69 and BESS with capacities of 1.75 MW, 0.5 MW, 0.75 MW, 2.75 MW, 0.25 MW, 5.75 MW, 0.25 MW, and 0.25 MW, respectively. The scenarios are as follows:

- Scenario 1 Wind power only: 1.00 MW wind, no PV installed
- Scenario 2 0.25 MW PV and 1.00 MW wind
- Scenario 3 0.50 MW PV and 0.75 MW wind
- Scenario 4 0.75 MW PV and 0.50 MW wind
- Scenario 5 PV only: 1.00 MW PV, no wind installed

The IEEE 69-bus system is a standard benchmark for distribution network studies, featuring 69 buses at a base voltage of 12.66 kV, with total loads of 3,801 kW and 2,694 kVAR, and a base apparent power of 10 MVA. Its minimum voltage is 0.9097 pu at bus 54, highlighting voltage drop issues. Compared to the IEEE 33-bus system, it is larger and more complex, making it ideal for testing advanced control strategies like BESS.

The results in Tables 5.11 and 5.12 show that the Fuzzy Multi-objective PSO algorithm effectively balances TVD and TSoC. Its fuzzy multi-objective PSO controller simultaneously handles system uncertainties and optimizes for multiple objectives, ensuring a balanced and adaptive response. This leads to better voltage regulation and BESS utilization, maintaining both voltage stability and SoC.

Figures 3.32 to 3.36 show how the BESS manages voltage control under different scenarios. The BESS absorbs excess energy during high solar or high wind output to prevent overvoltage and discharges during low renewable periods to support voltage levels. These results demonstrate that, with the proposed algorithm, the BESS effectively regulates voltage and improves distribution system reliability an essential function for modern grids with high renewable integration.

Table 5.11 The Maximum, Minimum, and Fuzzy Multi-Objective of Voltage Deviation

Scenarios	Minimum TVD	Fuzzy TVD	Maximum TVD
Scenario 1 Wind power only: 1.00 MW wind, no PV installed	0.4704	0.4997	0.6334
Scenario 2 0.25 MW PV and 1.00 MW wind	0.5705	0.5949	0.7395
Scenario 3 0.50 MW PV and 0.75 MW wind	0.6766	0.7043	0.8492
Scenario 4 0.75 MW PV and 0.50 MW wind	0.7792	0.8141	1.0094
Scenario 5 PV only: 1.00 MW PV, no wind installed	0.8979	0.9285	1.0874

Table 5.12 The Maximum, Minimum, and Fuzzy Multi-Objective of SoC Deviation

Scenarios	Minimum TSoC	Fuzzy TSoC	Maximum TSoC
Scenario 1 Wind power only: 1.00 MW wind, no PV installed	0.0827	0.3873	1.7769
Scenario 2 0.25 MW PV and 1.00 MW wind	0.1183	0.3563	1.7613
Scenario 3 0.50 MW PV and 0.75 MW wind	0.0904	0.3719	1.8434
Scenario 4 0.75 MW PV and 0.50 MW wind	0.0886	0.3486	1.8023
Scenario 5 PV only: 1.00 MW PV, no wind installed	0.0514	0.3379	1.8232

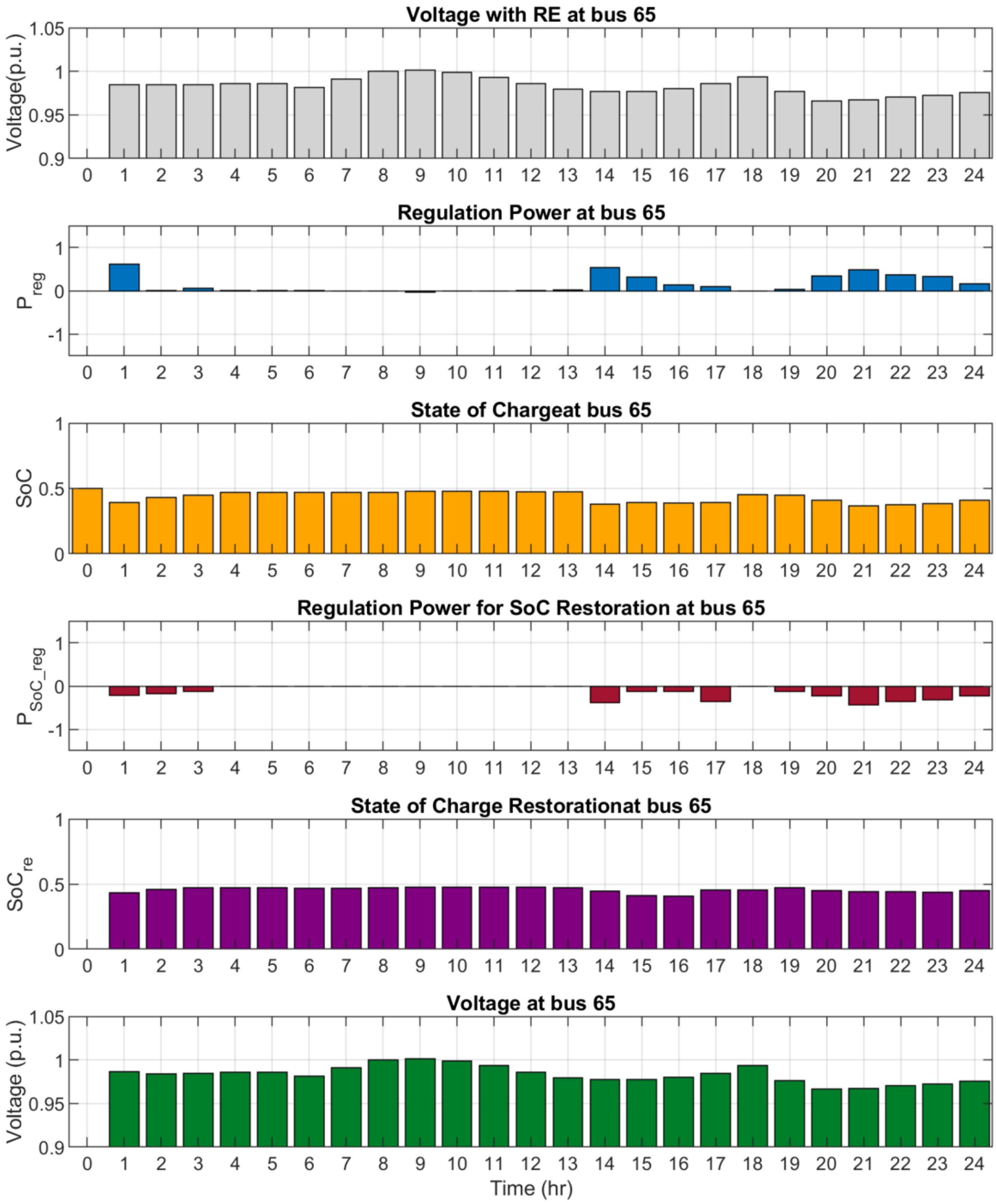

Figure 5.32 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 65 Scenario 1

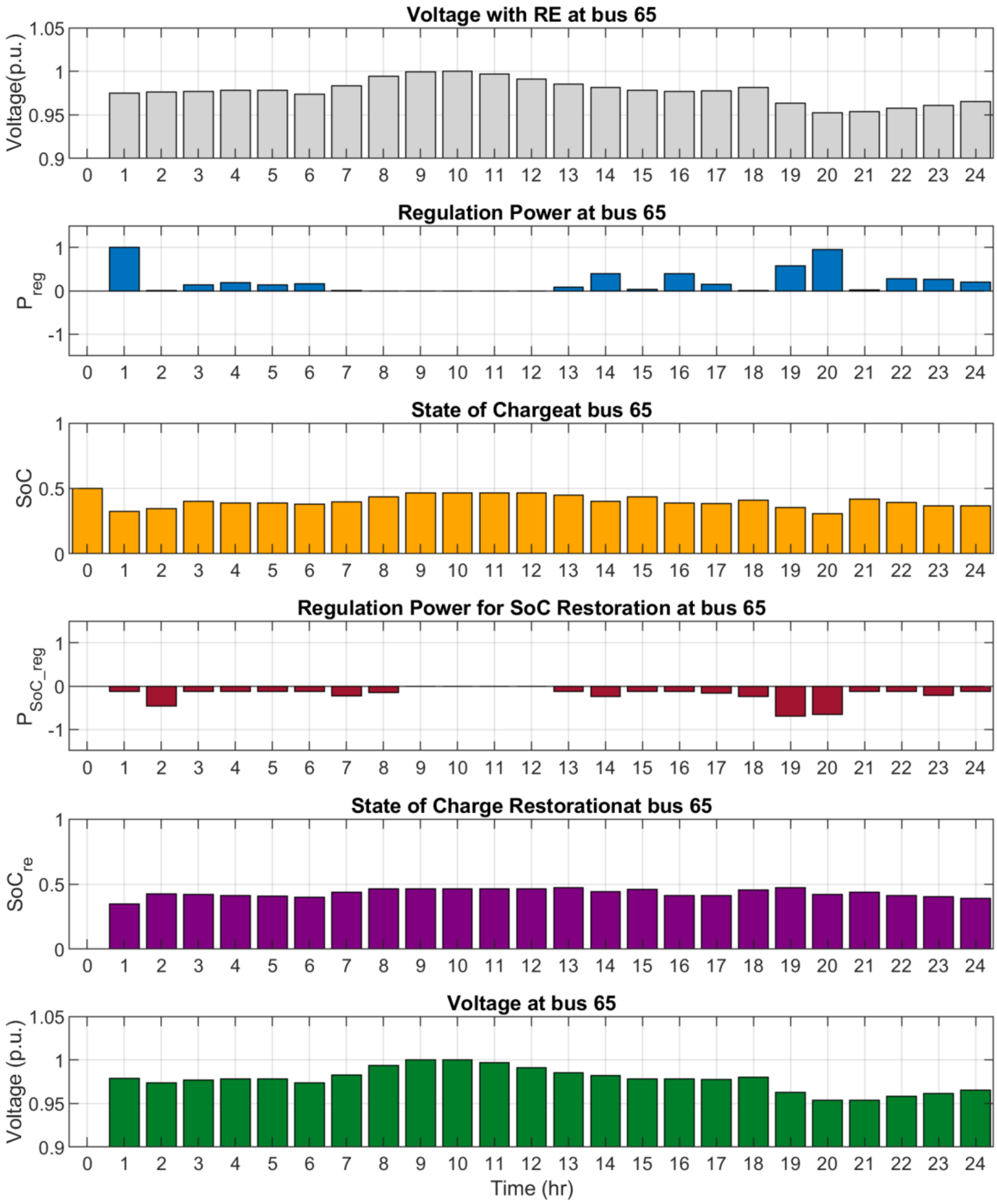

Figure 5.33 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 65 Scenario 2

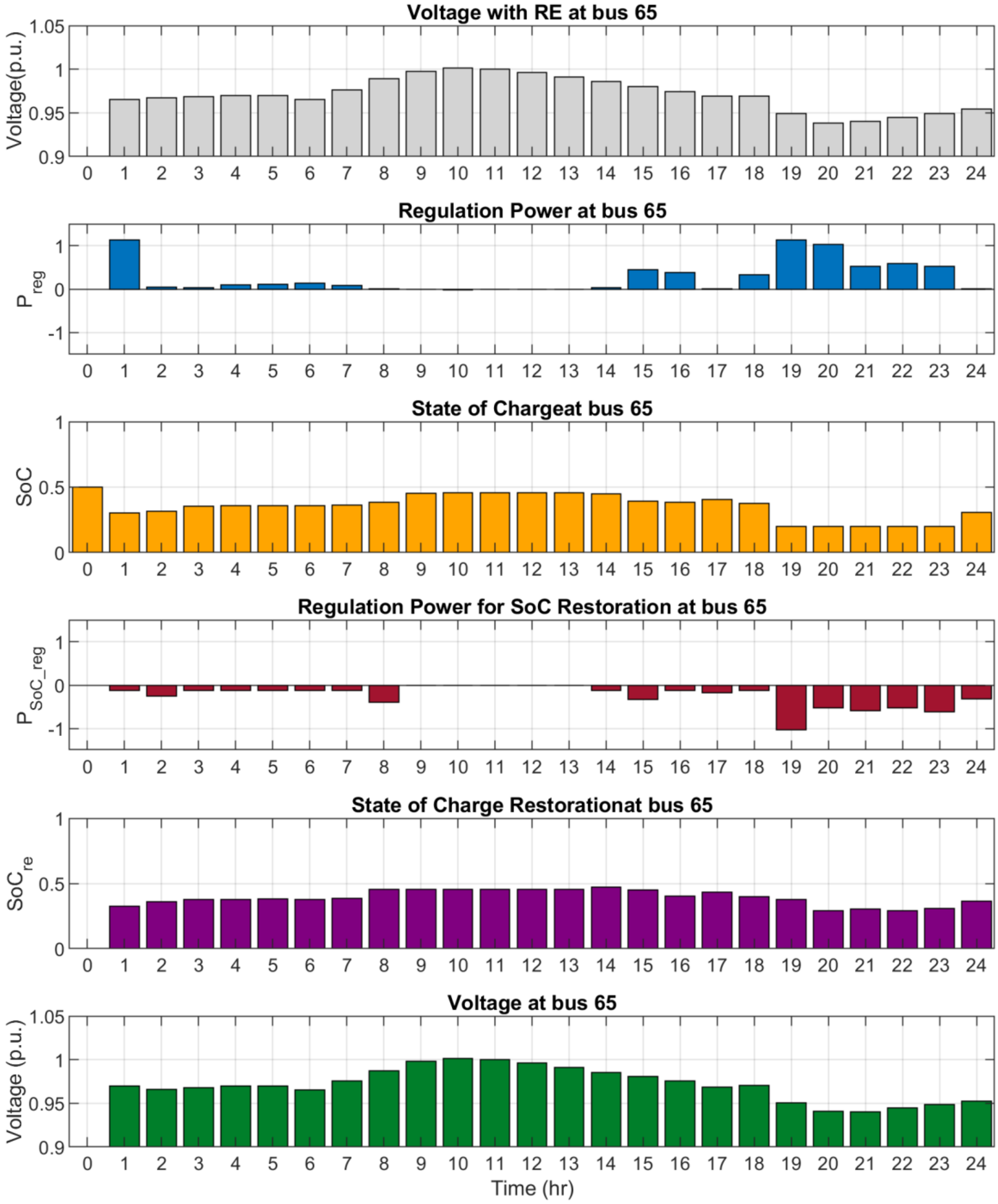

Figure 5.34 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 65 Scenario 3

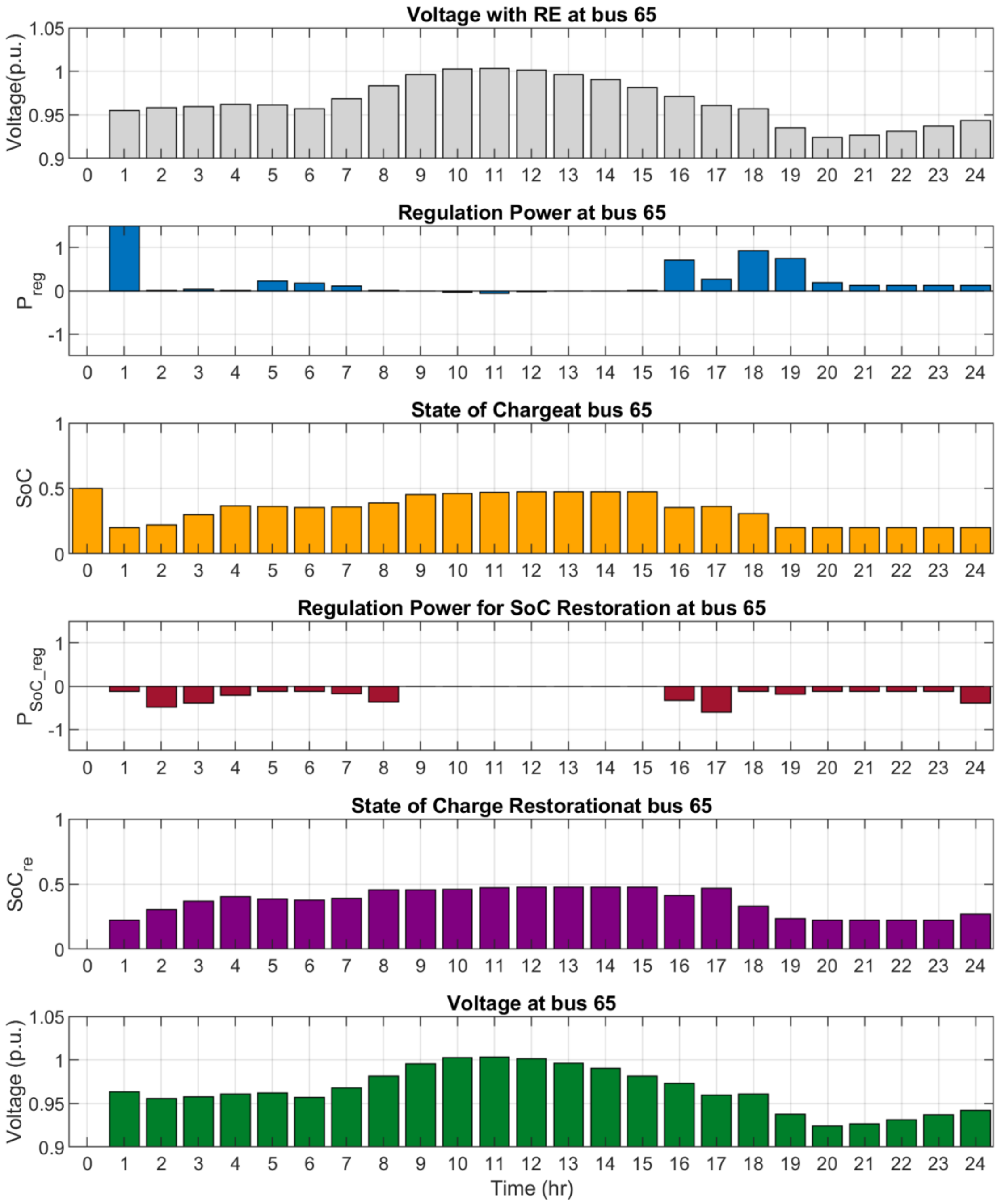

Figure 5.35 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 65 Scenario 4

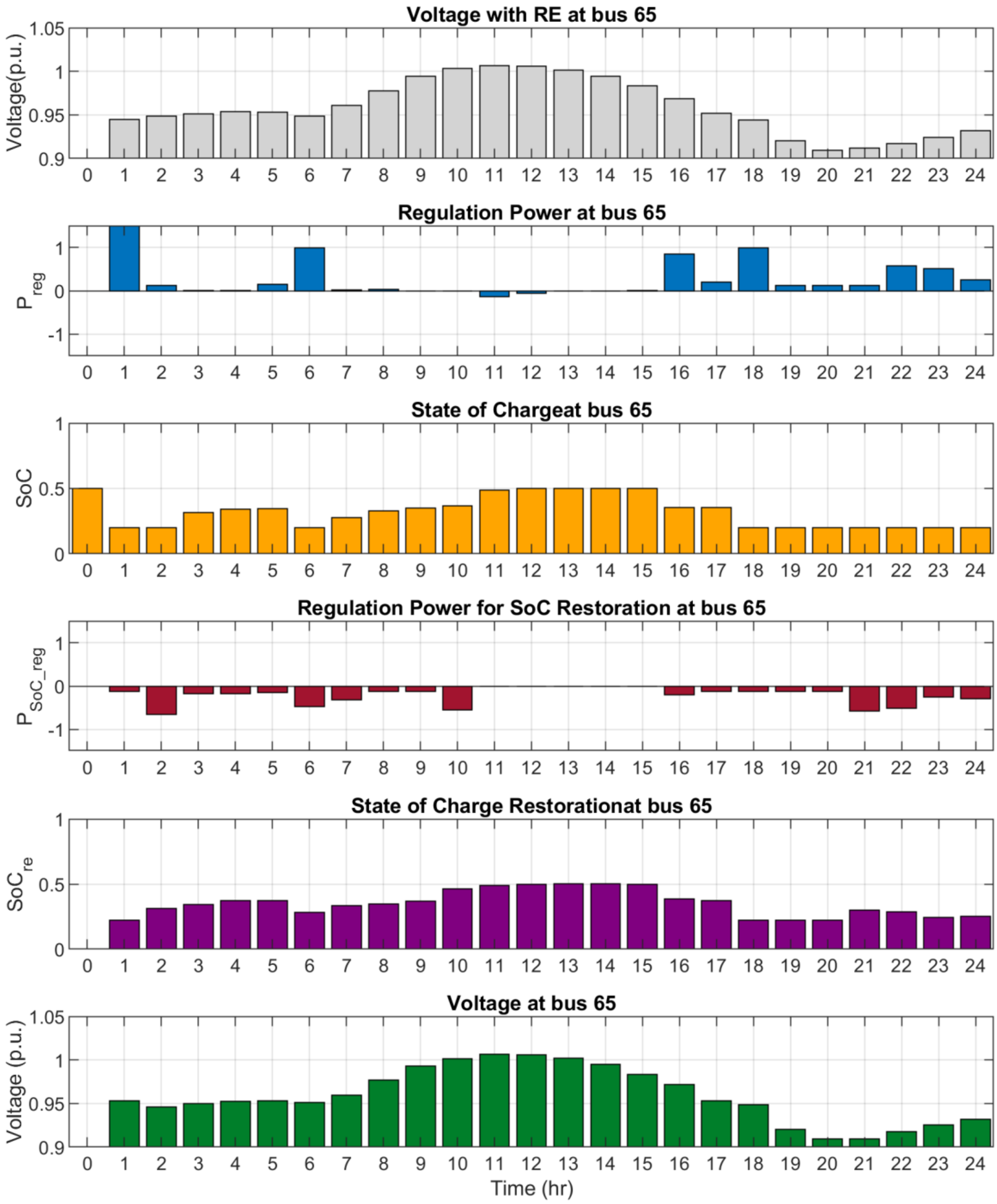

Figure 5.36 Time-Series Profiles of Voltage, Regulation Power and Battery SoC at Bus 65 Scenario 5

5.7 Chapter Summary

This chapter builds upon the previous chapter by introducing a more advanced control strategy for BESS that simultaneously manages voltage deviation and the battery's SoC. A key focus is the implementation of a SoC restoration mechanism, which ensures the BESS maintains an optimal charge level to guarantee its continuous availability for voltage regulation.

To address the competing objectives of minimizing TVD and TSoC, FMOO based on PSO was developed. This approach allows for a balanced trade-off between grid support and battery health. The methodology was rigorously tested on both the IEEE 33-bus and IEEE 69-bus systems under various scenarios with different combinations of PV and wind energy penetration.

The results consistently demonstrated the effectiveness of the FMOO-PSO controller. In all scenarios, the system successfully mitigated over-voltage during periods of high renewable generation and corrected under-voltage during low generation, while simultaneously guiding the SoC of the batteries back towards their nominal levels. The fuzzy multi-objective approach proved superior to single-objective optimization by finding a balanced solution that prevents excessive deviation in either voltage or SoC, thereby enhancing the overall reliability and resilience of the distribution network.