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Coordination of Distributed Generators and Energy Storage Systems

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Abstract

As the interconnection of distributed generation (DG) and energy storage system (ESS), the operation of DG/ESS should be optimized and coordinated. The intermittence of renewable energy and the error of the load forecasting, which is usually taken as the raw data of the global optimization algorithm, cause difference between the actual and the optimal operating status of the network. Feeder Control Error (FCE) is proposed based on the difference between the actual and the optimal net load of the network, and quantifies the operating error of the network. A coordinating control system of all the DG/ESS is proposed based on FCE, and 3 different control modes are put forwards. With the coordination system, the difference between the actual and the optimal net load are balanced by all the DG/ESS proportionally, and this reduces the operating error relative to the optimal operation status.

Keywords: *feeder control error, coordination control, distributed generation, energy storage system, operation optimization*

1. Introduction

With the technology development of smart grid, more and more Distributed Generator (DG) and Energy Storage System (ESS) are connected to the distribution line. The operating of DGs and ESS should be optimized and coordinated to promote the benefit of DG/ESS [1-2] and put off the upgrade of the network [3]. Many studies have been carried out on the optimization and the real-time control of DG/ESS. Wang [4] and Il-Yop [5] proposed a droop control based on P-f and Q-V characteristics, [6-9] proposed the coordinated real-time control of ESS to suppress the intermittence of the renewable energy. The operating of DG/ESS is optimized in [10-11] to reduce the peak-valley difference of the load. Optimization of wind-diesel system with ESS is proposed in [12], and the active management of DG/ESS are analyzed in [13-15] considering the line-loss, cost of electricity and reactive compensation.

The forecasted data of the power of load and renewable energy is usually taken as the raw data of the global optimization system of DG/ESS and the network. However, there is difference between the forecasted value and the actual value. Moreover, the global optimization is time-consuming and is executed in long-term cycle. The power of the load and the renewable energy are changed during the optimization cycle. This causes the different between the actual operating status and the optimal operating status of the network.

Feeder Control Error (FCE) is proposed based on the different between the actual net load and the optimal net load of the distribution line, and FCE quantifies the operating error of the whole network. Then a coordinating control system of all the DG/ESS is proposed based on FCE, and 3 different control modes are put forward. With the coordination of the system, the difference between the actual net load and the optimal net load is balanced proportionally by all of the DG/ESS. Finally, the coordinating control system based on FCE is demonstrated and verified in the case study.

2. Definition of Feeder Control Error and Consistent Net Load Control Mode

In the traditional distribution network, DGs/ESS are operated independently, lacking of coordination with each other, and the power intermittence of renewable energy generation is

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depressed with local ESS. With the technology development of smart grid, the amount of grid-connected DGs and the penetration of renewable energy increase, and the operation of DGs and ESS in the network should be coordinated.

In order to coordinate the operations of DGs and ESS, the operating status of the network needs to be estimated and quantified. There is usually a global operation optimization system for the network, and the optimal net load of the network is calculated, considering the load and weather forecasting. However, error existes in the load and weather forecasting, and this causes difference between the actual operating status and optimal operating status of the network. If the actual net load of the network is greater than the optimal one, it denotes heavier load or less power of DG than expected. On the opposite, the lighter actual net load denotes lighter load of greater power of DG than expected.

To quantify the actual operating status of the network, Feeder Control Error (FCE) is defined as the difference between actual net load and the optimal net load of the distribution line, as shown in (1):

$$FCE = P_{NL\_A} - P_{NL\_O} \tag{1}$$

Where P_{NL_A} is the actual value of the net load of the distribution line, which is got from the measurement system, and P_{NL_O} is the optimal value calculated by the global optimization system. The plus direction of P_{NL_A} and P_{NL_O} is to inject in the distribution line.

Accordingly, the governing equation of DG/ESS in consistent net load control mode based on FCE is shown in (2), where α_i is the power coordination coefficient of i^{th} DG/ESS, and ΔP_i is the power regulating amount. P_{i_O} is the optimal power of i^{th} DG/ESS at time T calculated by the global optimization system, and P_i is the regulating target.

$$\begin{cases} \Delta P_i(T) = \alpha_i \cdot \int_0^T \left(P_{NL\_A} - P_{NL\_O} \right) \cdot dt \\ P_i(T) = P_{i\_O}(T) + \Delta P_i(T) \end{cases} \tag{2}$$

The net load error of the distribution line is supposed to be P_{NL_Err} at $T = 0$, and after the coordination process the power regulating amount of DGs/ESS are calculated by (3):

$$\Delta P_i = P_{NL\_Err} \cdot \alpha_i \Big/ \sum_{j=0}^{N} \alpha_j \tag{3}$$

Where N is the count of power adjustable DGs/ESS. The net load error of the distribution line will be balanced by all of the power adjustable DGs/ESS proportionally to the power coordination coefficient, and the actual net load is kept consistent with the optimal value.

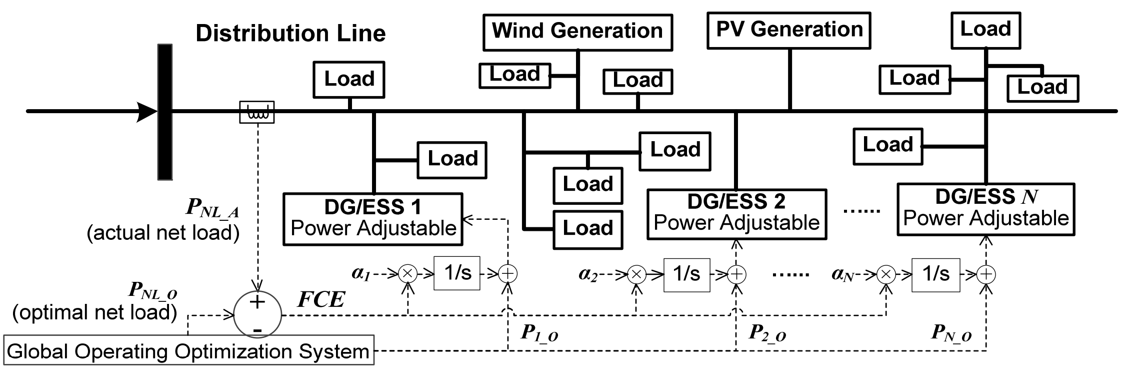

Figure 1. Coordination System Based on FCE in Consistent Net Load Control Mode

The coordination system based on FCE in consistent net load control mode is shown in Figure 1. The ideal optimal power of all the power adjustable DG/ESS in the distribution line are calculated by the global optimization system considering the load forecasting and renewable energy forecasting. As the error of the forecasting, there is unexpected power of loads or renewable energy generation. The error of the net load (FCE) is calculated and multiplied by the coordination coefficient, then the power regulation amount of DG is calculated with the integral of FCE (1/s in Figure 1). After the coordination, the unexpected net load is balanced by all of the power adjustable DGs/ESS, and the actual net load is kept consistent with its optimal value.

Considering that the global optimization algorithm is time-consuming, the application of the coordination system based on FCE can regulate the power adjustable DGs/ESS autonomously between the optimization cycle. The coordination system also suppresses the impact of the forecasting error on the operating status of the whole line.

3. Biased Net Load Control Mode Based on Feeder Control Error

All the unexpected power of the net load is balanced by the DGs/ESS in the network in the consistent net load control mode. However, the unexpected net load may exceed the regulating capacity of the DGs/ESS, therefore the biased net load control mode is proposed. The model of FCE in this mode is shown in (4):

$$FCE_i = \left(P_{NL\_A} - P_{NL\_O}\right)\cdot\frac{1}{K} - \left(P_{i\_A} - P_{i\_O}\right)\cdot\frac{1}{\alpha_i} \tag{4}$$

Where P_{i_A} and P_{i_O} are the actual power and optimal power of i^{th} DG/ESS, K is the deviation coefficient of the net load. FCE_i is the FCE for i^{th} DG/ESS, and the other variables have the same meaning with that in (1-2). The governing equation of DGs/ESS is (5), where $P_i(T)$ is the regulating target of i^{th} DG/ESS.

$$\begin{cases} \Delta P_i(T) = \int_0^T \left[\left(P_{NL\_A} - P_{NL\_O}\right)\cdot\frac{1}{K} - \left(P_{i\_A} - P_{i\_O}\right)\cdot\frac{1}{\alpha_i}\right]\cdot dt \\ P_i(T) = P_{i\_O}(T) + \Delta P_i(T) \end{cases} \tag{5}$$

After the coordination, the deviation of the net load (ΔP_{NL}) relative to its optimal value is calculated by (6), and the power regulating amount of i^{th} DG/ESS is calculated by (7).

$$\Delta P_{NL} = P_{NL\_Err}\cdot K \Big/ (K + \sum_{j=1}^{N}\alpha_j) \tag{6}$$

$$\Delta P_i = P_{NL\_Err}\cdot \alpha_i \Big/ (K + \sum_{j=1}^{N}\alpha_j) \tag{7}$$

According to (6) and (7), the unexpected net load P_{NL_Err} is balanced by both DGs/ESS and external grid (high-voltage distribution network or transmission grid) proportionally, and the actual net load has a deviation from its optimal value. The coordination system based on FCE in the biased net load control mode is similar to that in the consistent net load control mode.

4. Control Mode Considering the SOC Error of ESS

The energy storage system is different from the power adjustable DG. Not only the charging/ discharging power, but also the Status Of Charge (SOC) of ESS should be considered by the coordination system. The operation of ESS in a specific period of time (e.g., 24 hours) is optimized by the global optimization system. Correspondingly, the SOC in the period of time is also optimized. However, the SOC of ESS in the actual operation is different from the optimal SOC. Therefore, the coordination system based on FCE should take the SOC error into account, and reduce the SOC error.

The model of FCE considering the SOC error is shown in (8), where Soc_{i_A} , Soc_{i_O} are the actual SOC and optimal SOC of i^{th} ESS, and β_i is the SOC regulating coefficient.

$$FCE_i = \left(P_{NL\_A} - P_{NL\_O}\right)\cdot\frac{1}{K} - \left(P_{i\_A} - P_{i\_O}\right)\cdot\frac{1}{\alpha_i}P_{i\_\mathrm{Err}} + \left(Soc_{i\_A} - Soc_{i\_O}\right)\cdot\beta_i \quad (8)$$

The governing equation of ESS in the coordinating considering the SOC error is (9).

$$\begin{cases}\Delta P_i = \int_0^t \left[\left(P_{NL\_A} - P_{NL\_O}\right)\cdot\frac{1}{K} - \left(P_{i\_A} - P_{i\_O}\right)\cdot\frac{1}{\alpha_i}P_{i\_\mathrm{Err}} + \left(Soc_{i\_A} - Soc_{i\_O}\right)\cdot\beta_i\right]\cdot dt \\ P_i = P_{i\_P} + \Delta P_i\end{cases} \quad (9)$$

Supposing that the actual powers of the loads and all of DGs/ESS are the same as the forecasting power or the optimal power, and the SOC error of i^{th} ESS is Soc_{i_Err} , the power regulating amount of DG/ESS is calculated by (10) The governing equation of ESS considering the SOC error is (9), where ΔP_{NL} , ΔP_i and ΔP_j are the power regulating amount of the external grid, i^{th} ESS and other DG/ESS respectively.

$$\begin{cases}\Delta P_i = \frac{\alpha_i}{K}\cdot\Delta P_{NL} + \alpha_i\cdot\beta_i\cdot Soc_{i\_\mathrm{Err}} \\ \Delta P_i + \sum_{j\neq i}\Delta P_j + \Delta P_{NL} = 0 \\ \Delta P_j / \Delta P_{NL} = \alpha_j / K, \qquad j \neq i\end{cases} \quad (10)$$

Then (11) is derived from (10), where $A = \sum_{j=1}^{N}\alpha_j$.

$$\Delta P_i = \frac{A + K - \alpha_i}{A + K}\cdot\alpha_i\cdot\beta_i\cdot Soc_{i\_\mathrm{Err}} \quad (11)$$

If we want to reduce the SOC error of i^{th} ESS to 0 within the time ΔT , the value of β_i will be calculated as (12), in which E_i is the energy capacity of i^{th} ESS, and the other symbols have the same meaning as that in (4), (11).

$$\beta_i = \frac{E_i}{\Delta T}\cdot\frac{A + K}{\left(A + K - \alpha_i\right)\cdot\alpha_i} \quad (12)$$

According to (12), the value of β is directly proportional to the energy capacity of the ESS, and is inversely proportional to the time ΔT .

In this control mode, the unexpected net load is balanced by both external grid and all the DGs/ESS. And besides, there is an additional component in the power regulating amount to reduce the SOC error of ESS. If $Soc_{i\_\mathrm{Err}} > 0$, the additional component will increase ESS' discharging power or reduce the charging power. On the opposite, the discharging power will be reduced or the charging power be increased when $Soc_{i\_\mathrm{Err}} < 0$. The SOC error tends to decrease with the additional regulating component, and the speed of the decreasing depends on the value of β and the energy capacity of ESS.

5. Case Study

A distribution line with 8 loads and 1 wind generator is taken as a case, in which there are 2 grid-connected ESS and 2 power adjustable DGs. The topological connection of the network is shown in Figure 2. The electrical specification of DGs/ESS is shown in Table 1. The powers of loads and wind generator are shown in 0 and 0. The powers of load3, load6 and WG change with time.

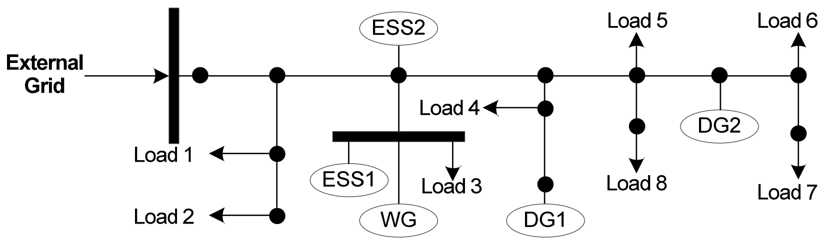

Figure 2. Topological Connection of the Network in Case Study

Table 1. Electrical Specifications of Power Adjustable DGs/ESS

Name	Rated Power	Energy Capacity	Planned Power	α
ESS1	80kW	160 kW*h	0kW	0.4
ESS2	80kW	400 kW*h	40kW	0.2
DG1	100kW	--	50kW	0.25
DG2	100kW	--	70kW	0.15

Table 2. The Power of the Loads

Name:	Load1	Load2	Load4	Load5	Load7	Load8
Power(kW):	61.5	82	53.5	130.5	93.5	101

Table 3. The Power of the Loads and Wind Generator at Different Time

	Time: 0-1m	1-2m	2-3m	3-4m
WG	120 kW	60 kW	120 kW	90 kW
Load3	60 kW	100 kW	60 kW	80 kW
Load6	90 kW	110 kW	90 kW	90 kW

The actual powers of Load1, 2, 4, 5, 7, 8 are equal to their forecasted power. The forecasted powers of WG, Load3 and Load6 are 120kW, 60kW and 90kW. As the power changing of WG, Load3 and Load6, there is difference between forecasted value and actual value, as shown in Figure 3. The power regulation ranges of ESS1,2 and DG1,2 relative to the their optimal power are $\pm 80\text{kW}$, $\pm 40\text{kW}$, $\pm 50\text{kW}$ and $\pm 30\text{kW}$.

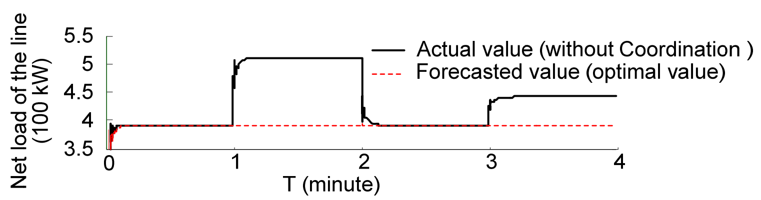

Figure 3. The Actual Value and Plan Value of Exchanged Power of ADN line

The coordination system is built with the Matlab Simulation, and the operations in different control modes are simulated.

5.1. Demonstration of the Consistent Net Load Control Mode

The coordination control system of ESS1 is shown in Figure 4, where "PE_Err" is the error of the net load, and "0.4" is the power coordination coefficient of ESS1. "PI" is proportion integral, "ESS1_P_Plan" is the optimal value of the power of ESS1, and "ESS1_Ctrl" is the control signal of ESS1 after the coordination. The coordinate control systems of ESS2, DG1 and DG2 are similar with that of ESS1.

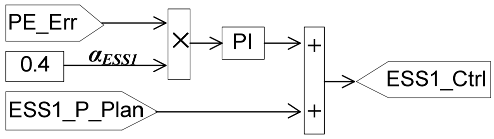

Figure 4. Coordinate Control System of ESS1 in Consist Exchanged Power Mode

The actual net load of the distribution line with the coordination system in consistent net load control mode is shown in Figure 5. The power of loads and wind generator changes at the time 1, 2, 3, and the operations of ESS1, 2 and DG1, 2 are regulated by the coordination system to keep the actual net load consistent with the optimal value. The actual powers of DG/ESS are shown in Figure 6, which shows that the powers of DG/ESS will increase when there are positive unexpected net load to balance the unexpected net load.

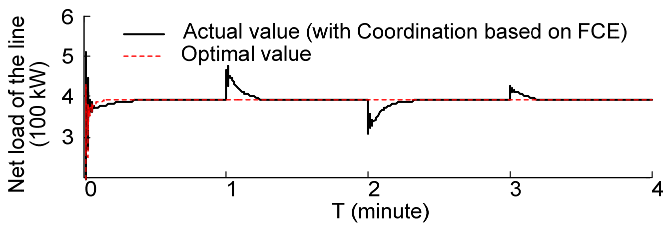

Figure 5. The Actual Value and Optimal Value of the Net Load in Consistent Net Load Control Mode

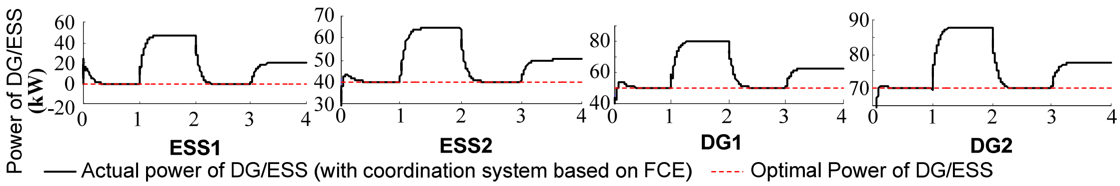

Figure 6. The Power of DG/ESS in Consistent Exchanged Power Control Mode

Table 4. Unexpected Power of Load and WG, and the Power Regulation of DG/ESS

	Time:	0-1 min	1-2 min	2-3 min	3-4 min
Unexpected power of Loads and WG:		0	120kW	0	50kW
The power regulation with the coordination system in consistent net load control mode	ESS1 :	0	48kW	0	20kW
	ESS2 :	0	24kW	0	10kW
	DG1 :	0	30kW	0	12.5kW
	DG2 :	0	18kW	0	7.75kW
Error of the net load after the coordination:		0	0	0	0

The power regulation of DG/ESS is shown in Table 4. During the time period $[1, \ 2\min]$ the unexpected power is 120kW, and the power regulations of ESS1,2 and DG1,2 are 48kW, 24kW, 30kW and 18kW respectively, which have the same proportion with their power coordination coefficient. The unexpected power is balanced by DG/ESS, and the actual net load with the coordination is equal to the optimal value.

5.2. Demonstration of the Biased Net Load Control Mode

The coordinate control system of ESS1 in biased net load control mode is shown in Figure 7, in which "1.0" is the deviation coefficient of the net load, and "ESS1_P_A" is the actual value of ESS1. The other symbols have the same meaning with that in Figure 4. The coordinate control systems of other ESS/DG are similar with that of ESS1.

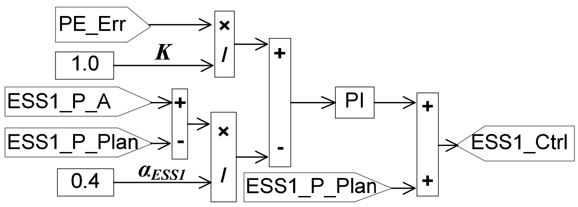

Figure 7. Coordinate Control System of ESS1 in Biased Exchanged Power Mode

The actual net load of the distribution line with the coordination system in biased net load control mode is shown in Figure 8. There is still deviation the actual net load with the coordination in the biased net load control mode from the optimal net load, and the deviation is smaller than that without the coordination system. The deviation of the net load after the coordination depends on the deviation coefficient of the net load (K). The power regulation of DG/ESS and the deviation of the net load are shown in Table 5, which shows that half of the unexpected power is balanced by DG/ESS and the rest is balanced by the external grid. The power regulation of DG/ESS and deviation of the net load have the same proportion with DG/ESS' coordination coefficient and the deviation coefficient of the net load, and this verifies the Equation (6), (7).

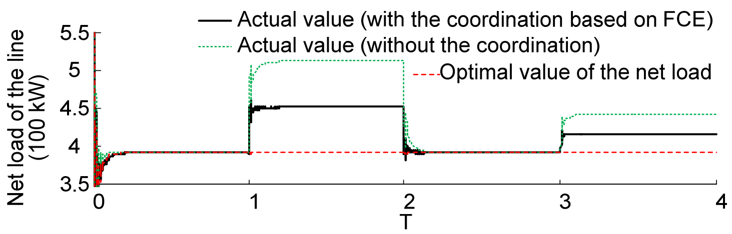

Figure 8. The Net Load of the Line in Biased Net Load Control Mode

Table 5. The Power Regulation of DG/ESS in Biased Net Load Control Mode

		Time:	0-1 min	1-2 min	2-3 min	3-4 min
Unexpected power of Loads and WG:			0	120kW	0	50kW
The power regulation with the coordination system in biased net load control mode		ESS1 :	0	24kW	0	10kW
		ESS2 :	0	12kW	0	5kW
		DG1 :	0	15kW	0	6.25kW
		DG2 :	0	9kW	0	3.75kW
Deviation of the net load after the coordination:			0	60kW	0	25kW

5.3. Demonstration of the Control Mode Considering the SOC Error of ESS

Supposing $\Delta T = 2$, the value of β is 2.5×10^5 according to the equation (12). The coordination control of ESS1 considering the SOC error is shown in Figure 9, in which "SOC1_A" and "SOC1_Plan" are the actual SOC and optimal SOC of ESS1. The other symbols have the same meaning with that in Figure 7. The coordination control of ESS2, DG1 and DG2 are the same as that in biased net load control mode.

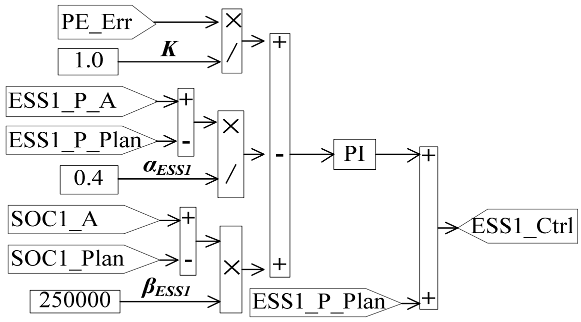

Figure 9. Coordinate Control of ESS1 Considering the SOC Error

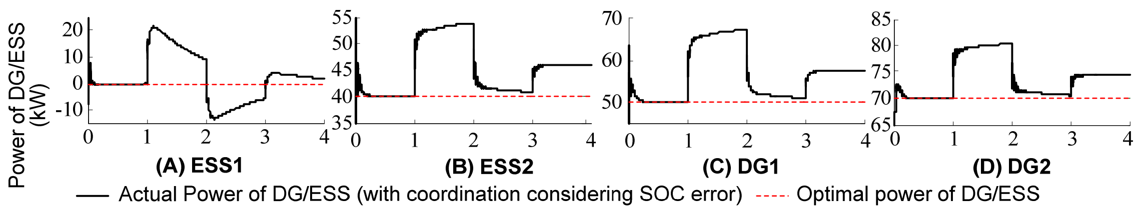

Figure 10. Power of DG/ESS with the Coordination System Considering SOC Error

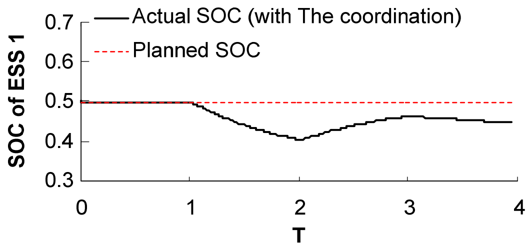

Figure 11. Actual SOC of ESS 1 with the Coordination System Considering SOC Error

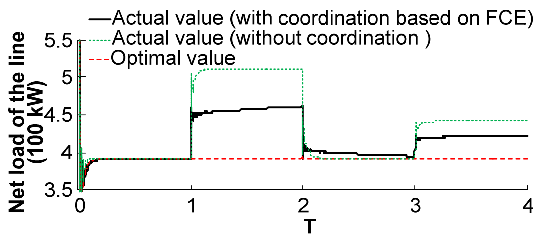

Figure 12. Actual Net Load of the Network with the Coordination System Considering SOC Error

The actual power of ESS1, 2 and DG1, 2 with the coordination system are shown in Figure 10, and the SOC of ESS1 is shown in Figure 11. The operating status of all DGs/ESS is the same as the optimal status during the time period of [0, 1]. During [1, 2] the loads increases and the power of WG decreases, and the powers of ESS1,2 and DG1,2 increase with the coordination control. The planned power of ESS1 is 0, and the planned SOC is 0.5. The actual SOC decreases as the discharging of ESS1 with the coordination (as shown in Figure 11). The SOC error is negative, and this cause an additional regulating component to reduce the SOC error. The discharging power decreases with the regulating component. During the time period [2, 3], the power of loads and WG are equal to their planned value, and correspondingly the power of ESS2, DG1,2 decrease to their planned power. As the actual SOC of ESS1 is lower than its planned value, ESS1 charge during [2, 3] to reduce the SOC error, and the charging power of ESS1 is balanced proportionally by ESS2, DG1,2 and the external grid.

The actual net load of the network with the coordination system considering SOC error is shown in Figure 12.

6. Conclusion

Feeder Control Error (FCE) is proposed in this paper based on the different between the actual net load and the optimal (planned) net load of the distribution line. FCE is an indicator of the actual operating status of the network, and based on FCE a coordination control system is proposed to coordinate the operating of all the DG/ESS. 3 coordination control modes are proposed: consistent net load control mode, biased net load control mode and the control mode considering the SOC error of ESS. The coordination system in the 3 control modes are demonstrated and verified in the case study.

There are errors between the forecasted load/renewable energy and the actual load/renewable energy. With the coordination system, the unexpected load and the fluctuation of the renewable energy will be balanced by all the power adjustable DGs/ESS proportionally according to their coordination coefficient, and this reduce the impact caused by the forecasting error and the fluctuation of the renewable energy.

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