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Doctoral Dissertation

Voltage Control via Residential Load Scheduling in Next Generation Power Distribution System

次世代配電システムにおける住宅負荷スケジューリングによる電圧制御に関する研究

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Abstract

Along with the development of smart grid, the power distribution system is changing greatly in recent years. Distributed generators (DGs) such as residential rooftop photovoltaic systems are integrated into the power distribution system. For the environmental concerns, electric vehicle (EV) technology is developing quickly. When the PV and EV are popular in the residential area, the voltage control in distribution system is becoming more complicated and challenging. High degree of PV penetration may cause overvoltage problem, while low voltage violation problem may happen when a large number of EVs are charging at the same time. On the other aspect, home energy management system (HEMS) and community energy management system (CEMS) are developed at demand side to visualize the energy usage in the home, control the smart household appliances automatically and manage the home energy consumption more efficiently.

This research aims to introduce load scheduling method for voltage control in next generation power distribution system. A central CEMS and multi-sub-CEMS model in the distribution system is proposed to utilize the load scheduling for voltage control. In this structure, central CEMS is the main controller, and each sub-CEMS independently and concurrently manage its covering customers' schedulable loads (SLs) for the voltage control. A day-ahead load scheduling and a real-time load rescheduling method are proposed based on the central CEMS and multi-sub-CEMS structure. The day-ahead scheduling is formulated as an optimization problem and genetic algorithm (GA) is applied to solve the optimization. The objectives are to maximize customers' profit and reduce the distribution system voltage violation frequency. The starting time of the SLs are decided through GA in the day-ahead scheduling. In the real-time operation, a coordinated real-time voltage control of an on-line tap changer (OLTC) and CEMS is proposed. The main objectives of this control are to 1) relieve the stress in the OLTC tap operation by rescheduling the SLs working time, and to 2) follow the day-ahead schedule as much as possible. The minimum capacity of SLs rescheduling performed by each sub-CEMS is formulated as a nonlinear scheduling optimization problem, which is solved by a sequential search method named voltage ranking-based load combination search algorithm (VRLCS).

The proposed methods are first simulated on a 12-customer small distribution system model and then on a 1800-customer large normal Japanese distribution system model. The simulation results validate the effectiveness of the proposed methods. Besides, reactive power generated by PV inverter is also applied in the overvoltage regulation. At last, the value in voltage regulation of the proposed system is carried out by calculating an equivalent SVC capacity.

With the development of smart grid, demand side management (DSM) is recognized as an important part in the next generation power distribution system. The load scheduling program in the DSM introduced by this research can be a good supplement for voltage control in next generation distribution system and can help save a large amount of control device investment.

Key words: Power distribution system, voltage control, CEMS, load scheduling

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Table of Contents

List of Figures

List of Tables

Abbreviations

Abbreviation	English name
AMI	Advanced metering infrastructure
CEMS	Community energy management system
DER	Distributed energy resources
DG	Distributed generation
DR	Demand response
DSM	Demand side management
DSO	Distribution system operator
EMS	Energy management system
ESS	Energy storage system
EV	Electric vehicle
FIT	Feed-in tariff
GA	Genetic algorithm
GECN	Grid explicit congestion notification
HEMS	Home energy management system
METI	Ministry of economy, trade and industry
min	Minute
NEDO	New energy and industrial technology development organization
ODL	On-demand load
OLTC	On load tap chanter
PF	Power factor
PV	Photovoltaic

S	Second
SC	Shunt capacitor
SL	Schedulable load
SR	Spinning reserve
SR	Shunt reactor
SVC	Static var compensator
SVR	Step voltage regulator
TOU	Time of use
V	Volts
V2G	Vehicle to grid

Chapter 1 Introduction

1.1 Next generation power distribution system

1.1.1 Power distribution system

Electric power system consists of generation, transmission, and distribution functions. Electricity is normally generated at 11-25 kV in a power plant, and then the voltage is step-up in a high voltage substation and delivered through transmission lines. A sub-transmission network connects the high voltage substations to the distribution substations. The distribution system ultimately supplies the electricity to the end consumers' loads [1],[2].

The range of primary distribution voltage is usually from 3.3 to 11.4 kV in Japan. Some large consumers are fed directly from the primary distribution voltages, while most of the commercial and residential consumers are connected to the secondary distribution network. The distribution voltage is reduced to low level by the transformer. The secondary distribution network serves most of the customers at levels of 100 V, single-phase, two-wire; 200/100 V, single-phase, three-wires; or 400Y/230 V, three-phase, four-wires in Japanese distribution system. The power for a typical home is derived from a pole transformer that reduces the primary feeder voltage to 200/100 V using a three-wire line [3].

With the technology development, power distribution system is changing greatly in nowadays. Distributed generations (DGs), including solar power and wind power, are integrated into the electric power distribution system. In former conventional distribution system, power flows from the substation to end consumers. After the introduction of DGs, power flow becomes bidirectional. Since the environmental concerns, electric vehicle (EV) technology is developed for reducing the greenhouse gases emission. EV battery becomes a new type of load in distribution system. The charging and discharging of EV battery may bring both great challenges and opportunities to the power distribution system. Furthermore, application of demand side management (DSM) technique has become attractive owing to its potential to more efficiently manage the energy consumption at demand side.

1.1.2 Integration of DG

DGs refer to a variety of small scale generations, including biomass, biogas, solar power, wind power and so on, which are connected in the distribution system. Different from the conventional centralized power stations, DG systems are decentralized and close to the end users. In some cases, DGs are utilizing more flexible technologies and generating less environmental influence [4].

Developing renewable energy technology has become an important national strategy in many countries. For example, the Denmark government decided to complete the total energy supply to 100% renewable energy by the year of 2050 [5]. After the great east Japan earthquake in 2011, the Japanese government attaches great importance to renewable energy development. According to the latest long term energy plan made by Japan's Ministry of Economy, Trade and Industry (METI), the renewable energy share target of 2030 is 22-24%, which is double than the current level (see Fig. 1.1) [6].

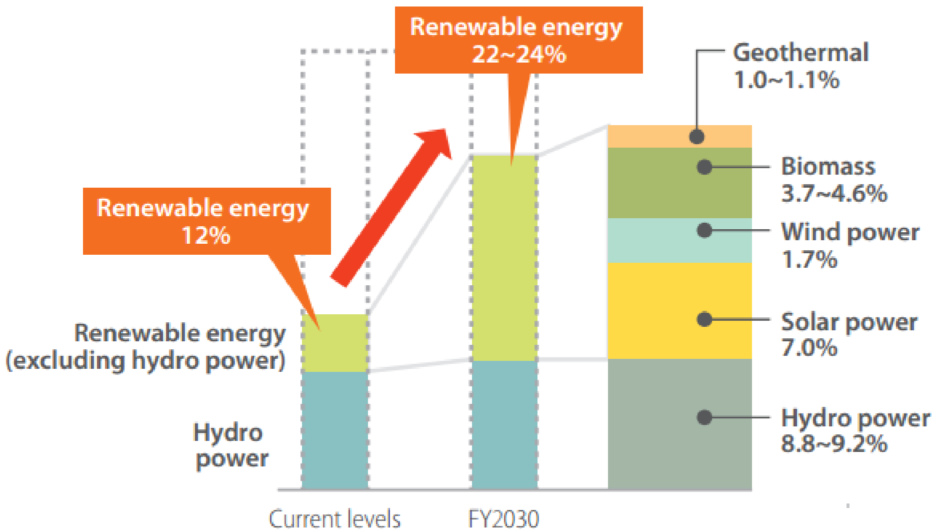

Fig. 1.1 Target in 2030: double increase from current levels [6]

Solar power is the most important one among the renewable energy recourses. Photovoltaic (PV) power generation, which converts sunlight into electricity with no pollution, has been regarded as one of the most excellent renewable energy resources. Solar PV gains a growth of more than 50 GW new capacity increment in 2015 worldwide. Total global PV capacity grows from 5.1 GW in 2005 to 227 GW in 2015 worldwide (see Fig. 1.2) [7].

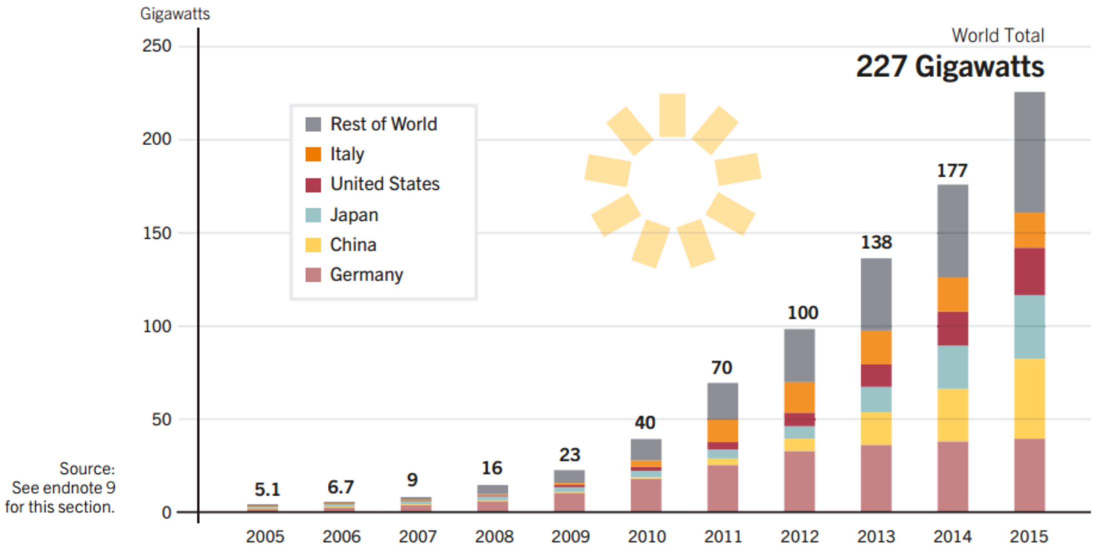

Fig. 1.2 Solar PV Global Capacity, by Country/Region, 2005–2015 [7]

In Japan, around 11 GW PV systems are connected into the grid in 2015, and the total capacity is around 34.4 GW [7]. To reach the Japan 2030 target, the largest capacity increment of renewable energy will come from PV. According to Fig. 1.3 [8], the capacity of PV will be 7 times of that in 2013.

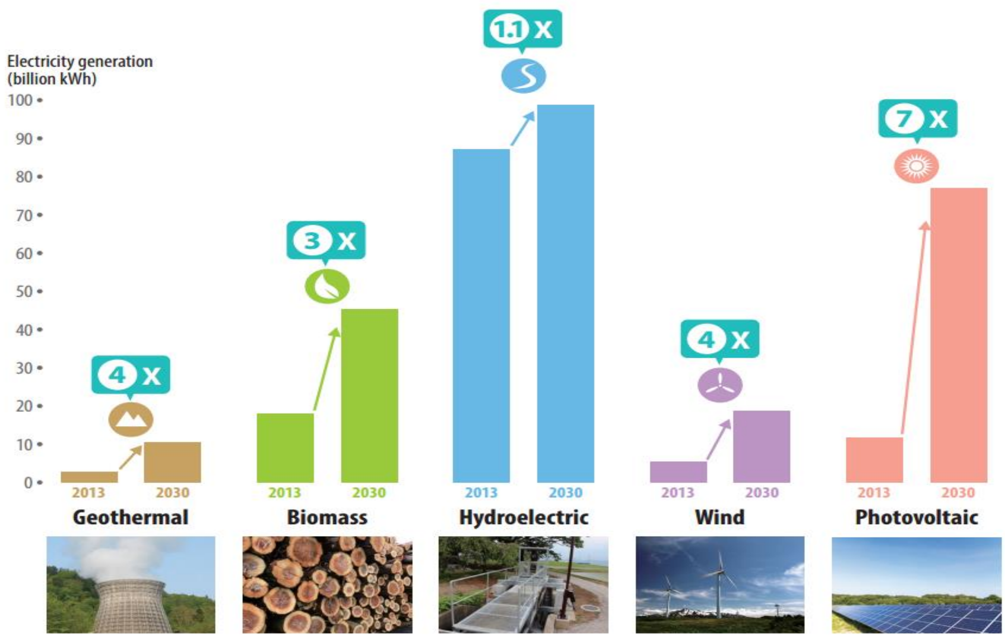

Fig. 1.3 Expanding Renewable Energy [8]

Many countries had made a feed-in tariff (FIT) in order to accelerate the development of renewable energy. Under the FIT, a renewable energy producer can sell the surplus electricity to the electric utility at a fixed price for a long-term period (usually 10 years or 20 years). In Japan, the surplus electricity purchase price for solar PV energy is 42 yen/kWh in 2012, which is much higher than the normal electricity consumption price around 27 yen/kWh. Since the surplus electricity purchase system was introduced in 2009, the introduction of PV power generation in Japan has largely increased [9].

In short, a large capacity of DGs will be installed in the distribution system, especially rooftop PV in residential area. However, the high degree of penetration of residential rooftop PVs in traditional distribution networks would generate reverse power, which will potentially raise the voltage upper to the high limit.

1.1.3 Integration of EV

Environmental concerns are an important topic in the energy field recently. EV technology is being developed for the purpose of reducing the emission of greenhouse gases. In recent years, EVs take a great increment in the personal vehicle market. According to a report of the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), the researchers found that electric vehicle is making significant increment. In 2015, the number of plug-in EVs increased worldwide by almost 750,000 to around 1.3 million. The EVs number of different countries are shown in Fig. 1.4 [10].

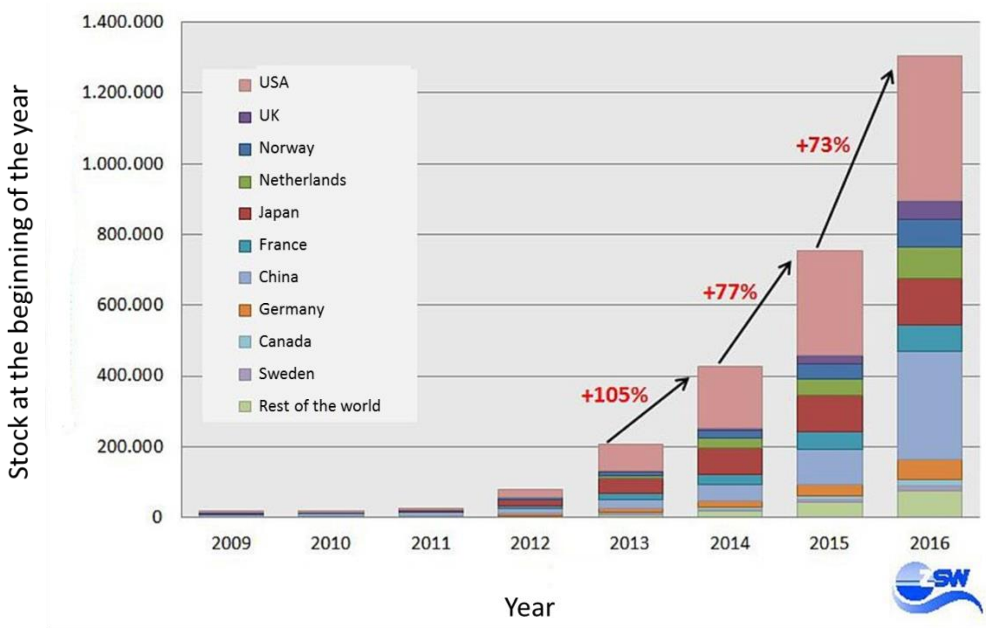

Fig. 1.4 EVs number of different countries [10]

The high penetration of EVs will bring potential challenges to electric utilities especially at the distribution system. For of the habit of most people, they may charge their EV battery in the evening after arrived home. If a large amount of EVs were to connect to power grid at the same time it would create a new load peak in the existing electricity grid. Furthermore, some other impacts on the distribution system may happen: power demand may exceed distribution transformer ratings; line current may exceed line ratings; and voltages at customers' points of connection may fall below the low limit [11].

However, in case the EV charging can be well coordinated, the EV batteries can perform an important role in the smart grid. If EVs are connected into the power grid when they are not in use, there is a potential for utilizing the EV battery to discharge electricity into the grid during peak load periods. This vehicle-to-grid (V2G) connection can supply a distributed spinning reserve [12]. Furthermore, if the EV battery has available capacity, it can also absorb the reverse active power generated by DG for avoiding the voltage rise program.

1.1.4 Energy management system (EMS)

Home energy management system (HEMS) is developed to visualize the energy usage in the home, control the smart household appliances automatically and manage the home energy consumption more efficiently. According to the report made by the National Strategy Office of Japan, all of the Japanese houses will be installed with a HEMS in the year of 2030 [13]. Many large companies in Japan such as Hitachi, Panasonic, Mitsubishi and so on have developed a HEMS product and installed in customers' houses [14]–[16]. The Fig. 1.5 shows the structure of HITACHI HEMS. According to the design of HITACHI HEMS product, the HEMS will cooperate with the community energy management system (CEMS) to utilize renewable energy such as PV. The smart household loads such as water heater, EV and energy storage system can be automatically controlled by HEMS to effectively utilize the renewable energy. Furthermore, HEMS can contribute to the peak shaving with load shifting according to the information from CEMS.

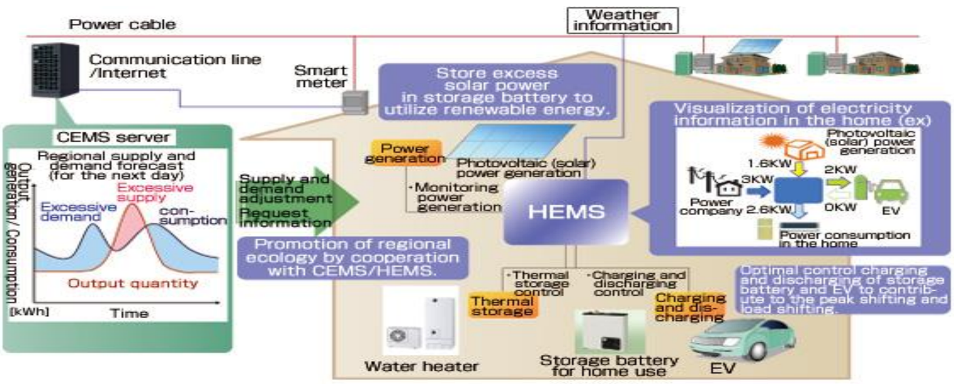

Fig. 1.5 Cooperation of CEMS and HEMS for the total efficient energy using [16]

With the development of HEMS, customers can receive more convenience and save electricity expense by letting the HEMS automatically control the household appliances. In other words, home energy consumption can be managed more efficiently. From the power system perspective, peak load shaving can be realized by the assistant of CEMS and HEMS. More renewable energy can be integrated into the power system if the power output can be managed properly.

The Japan METI has proposed a structure of smart community, which is shown in Fig. 1.6 [17]. According to the plan, a smart community makes full use of wind power, solar power and other renewables to generate electricity. The structure will make an energy network which possibly connects home, commercial buildings, and transportation systems. In the smart community, information technology will be utilized for balancing the supply and demand. It is assumed that there will be a control center in the smart community, which forecasts energy demand and electricity output based on historical data and weather condition. When the electricity demand exceeds the forecast, the control center can send signal to homes to facilitate the demand response, for example, avoid electricity consumption or change to low energy consumption mode. In this way, the responded homes can earn profit, and the whole society can save energy and reduce CO2 emission.

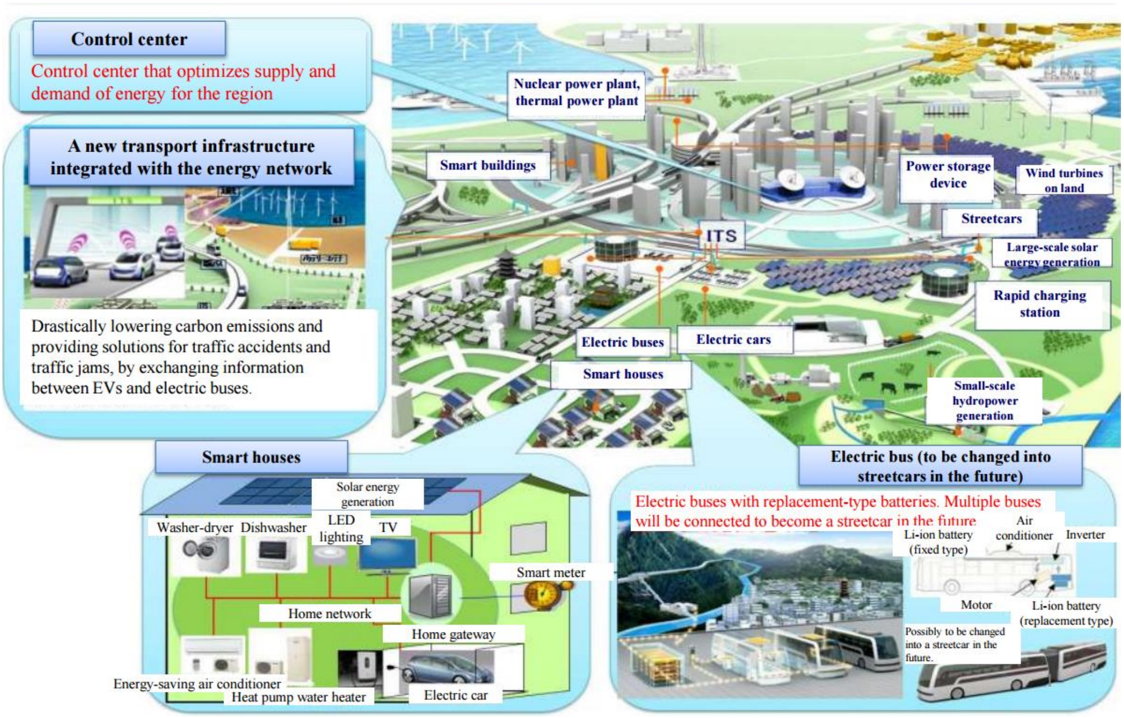

Fig. 1.6 Smart community in 2030 [17]

1.1.5 Demand side management (DSM)

DSM is to manage the energy consumption more efficiently, which is recognized as an important part in the future power system. It ranges from improving energy efficiency by using better materials, over smart energy tariffs with incentives for certain consumption patterns, up to sophisticated real-time control of distributed energy resources [18]. The reference [18] classified DSM into following four categories depending on the timing and the impact of the applied measures on the customer process (see Fig. 1.7).

a) Energy Efficiency.

b) Time of Use (TOU).

c) Demand Response (DR).

d) Spinning Reserve (SR).

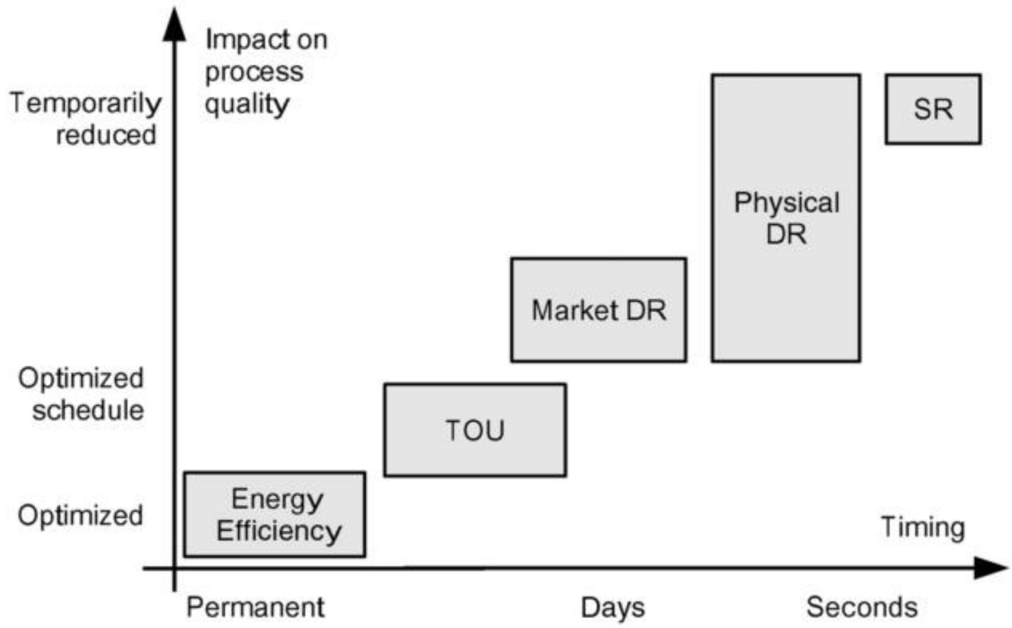

Fig. 1.7 Categories of DSM [18]

Energy efficiency methods are to utilize the power energy more efficient and therefore to save the energy consumption. TOU tariffs offer a higher price at peak load periods to encourage consumers to arrange their loads working time to minimize electricity expense. The market DR is that the DR relies on certain electricity markets, while physical DR is related to emergency signal. SR is implemented by loads. Loads can act as “virtual” (or negative) spinning reserve if they can cooperate their scheduling with the grid instruction. The objective of DSM is not aim to reduce the total energy consumption, but only to influence customers’ consumption patterns.

Usually, the purpose of DSM is to encourage the customers to use less electricity during peak time, and to move the load to off-peak times. This procedure does not change the total energy consumption, but by cutting down the peak demand, the power electricity company can reduce the need for investments in networks and power plants for meeting peak demands.

The application of DR through electricity price is in process nowadays. Day-ahead electricity market and hourly real-time electricity market have already developed in some countries [19]–[21]. With the price signal, customers can shift their loads from higher price period to lower price time [22]–[24]. In America, customers can save electricity expense with load scheduling by joining the day-ahead market and hourly real-time market through electricity retailer companies. According to the information from ComEd, an electricity company in the US, negative price sometimes offers to customers in real-time hourly market. The reason is that in the market, when electricity supply is far greater than demand, some types of electricity generators cannot or prefer not to reduce electricity output for short periods of time when demand is insufficient, and as a result some generators may provide electricity to the market at prices below zero [25].

The DR program obviously benefits for both electricity companies and consumers [26]. Currently, the application is still with hourly level, and it is not feasible in minute level until new technologies become available, like a smarter energy management system and rapid communication network. However, with the emergence of smart grid, bidirectional advanced metering infrastructure (AMI) is expected to be installed in the power system. Information transmission technology in nowadays is speedy, stable, and still on developing. If refer to a normal residential 10 M speed ADSL broadband, 125 KB data can be transported in 0.1 s. The information amount in power system is relative small comparing to video or audio information, so real-time communication will be not a difficult technology in smart power grid. In the near future, smart meter and HEMS will be installed in many residential houses. Customers can apply these machines to manage household scheduling automatically and optimally. Thus, DSM will become more efficient in the near future. Most of existing DSM programs are designed for cutting the peak demand and emergency conditions. However, the more efficient DSM will be also helpful for integrating more DG and EV in next generation distribution system.

As mentioned before, the growing penetration of DG and EV will bring various new challenges to the distribution system. However, within DSM programs, customers can be able to assist with dealing these new challenges. For example, DR can encourage customers to start their loads when PV output is high during the daytime; within DSM, customer’s EV charging can be moved to night time and scheduled cooperatively to avoid the new peak demand and voltage deviation. Furthermore, the

EV battery or energy storage system in customer's side can be utilized to smooth the intermittent of DG output [27]. A research found that the residential cooling DR resource is large and well-matched to mitigate the integration challenges of PV [28]. An integrated methodology that considers renewable DG and DR as options for planning distribution systems is proposed in [29]. The study indicates that the joint planning of DR and DG has demonstrated a super additive effect in terms of environmental benefits than integrating DG independently. A methodology for day-ahead energy resource scheduling for smart grids considering the intensive use of distributed generation and V2G is proposed in [30]. The study shows that with the proposed DR programs for EVs, the operation costs from the network operator point of view can be reduced. The survey of [31] shows that DR will play a major role in the smart grid implementations.

In short, the DSM program, which can help maintain power system reliability and flexibility, will play a more important role in next generation distribution system.

1.1.6 Image of the next generation power distribution system

With the development of smart grid, the next generation power distribution system will achieve seamless integration of DG, EV, energy storage system, and DSM program, and therefore becomes highly intelligent system. The image of the next generation power distribution system can be shown through Fig. 1.8 [32].

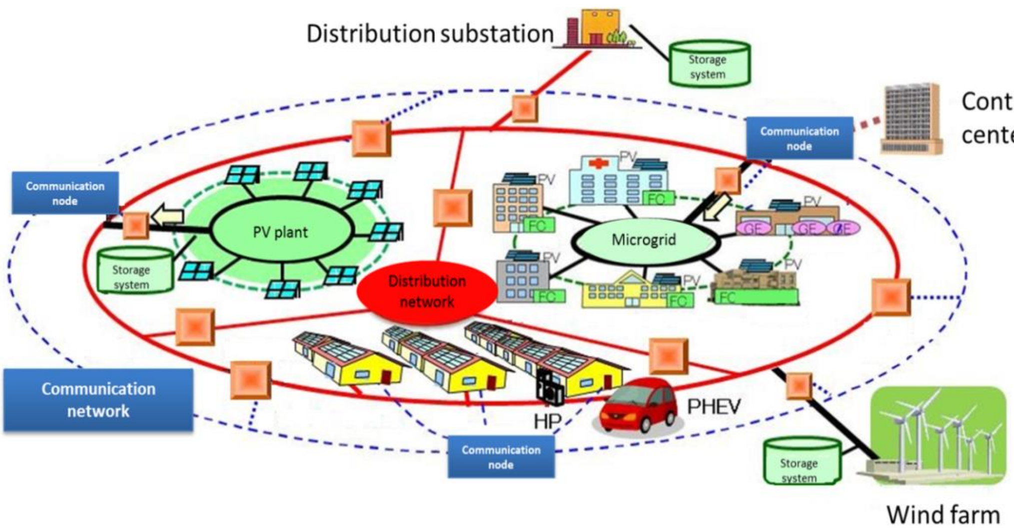

Fig. 1.8 Image of advanced electrical energy system [32]

Some key features of this advanced power distribution system are:

1) Integration of DG energy resources.
2) Integration of energy storage system.

3) Plug of EV, PHEV.
4) Bidirectional and reliable communication network.
5) Application of EMS.

1.2 Voltage control in next generation distribution system

1.2.1 Admissible voltage range in distribution system

Electricity is distributed to end consumers in a pre-defined voltage, for example, the single phase standard voltage in Japan is 100 V, and in North American is 120 V, while in most of the other countries are 220 or 230 V. Since voltage drops along with the distribution line, it is impossible to control the voltage at all consumers' side at the standard value. In fact, consumers are serviced the voltage with an admissible range instead of a specific value. For example, the admissible voltage range in Japan is 95 – 107 V. Voltage lower than the low limit (95 V) or higher than the high limit (107 V) would harm consumers' appliances.

As mentioned before, the large penetration of PV and EVs would raise or drop the distribution system voltage significantly. The voltage may be raised upper to the high limit when the PV output is much larger than the consumption power in a good irradiation condition during the noon time. When large amount of EVs are charging at the same time, the voltage may be dropped under the low limit. As a result, the DSO should deal with overvoltage problem and low voltage problem separately at different time period.

1.2.2 Overvoltage problem

In a traditional distribution system, power flows from the substation to the end customers; thus, the voltage drops along the distribution line. After the introduction of DGs, reverse power flow occurs when the DG output is larger than the power consumption. In a distribution system with high PV penetration, reverse power flow would raise the node voltage during daytime. To explain this fact, a diagram of a simplified distribution system model is shown in Fig. 1.9.

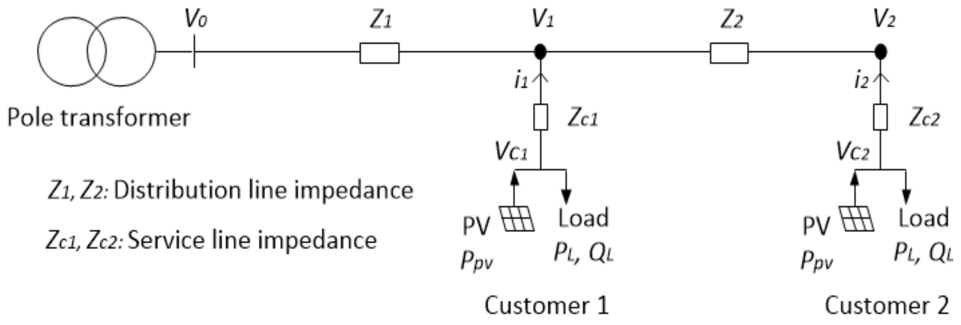

Fig. 1.9 Simple distribution system model with two customers

In the figure, two customers with PV installation are connected to a pole transformer at different locations. For simplicity, the distribution line impedances Z_1 and Z_2 are the same, and the service line impedances Z_{c1} and Z_{c2} are equal to $R + jX$. Similarly, the customer PV and load are assumed to be the same, where load power $S = P_L + jQ_L$ and the PV power is P_{PV}. The voltages at the pole transformer, customer 1, and customer 2 are V_0, V_{c1}, and V_{c2}, respectively. V_1 and V_2 are the voltages at the connection points of customers 1 and 2, whereas i_1 and i_2 are the service line currents of customers 1 and 2, respectively. With this model, assuming a day with good sunlight, the PV power is greater than the customer load consumption, i.e., $P_{PV} > P_L + XQ_L/R$. Thus, reverse power flow occurs.

Assuming that the positive current direction is from the pole transformer to the customers, the approximate voltage drops at the service line of customers 1 and 2 are negative and expressed in (1-1) and (1-2). Approximate V_{c1} and V_{c2} are expressed in (1-3) and (1-4).

$$\Delta V_{c1} = -Z_{c1} i_1 \approx \frac{R(P_L - P_{PV}) + XQ}{|V_{c1}|} \tag{1-1}$$

$$\Delta V_{c2} = -Z_{c2} i_2 \approx \frac{R(P_L - P_{PV}) + XQ}{|V_{c2}|} \tag{1-2}$$

$$V_{c1} = V_1 - \Delta V_{c1} \tag{1-3}$$

$$V_{c2} = V_2 - \Delta V_{c2} \tag{1-4}$$

In the above conditions, V_2 is larger than V_1, and their approximate values are expressed by (1-5) and (1-6).

$$V_1 = V_0 - Z_1(i_1 + i_2) \tag{1-5}$$

$$V_2 = V_1 - Z_2 i_2 \tag{1-6}$$

We can see from the above equations that the voltage at customer 2 is higher than that at customer 1 when their load and PV profiles are the same. Customer 2 will first suffer from overvoltage if the reverse power keeps on increasing. At this time, customer 2 is required to reduce his PV generation output by some voltage regulation strategies.

Because of the physical structure of distribution network, voltages at nodes farther from the distribution substation tend to be more volatile than those in other nodes. As a result, the overvoltage will happen more frequently at the location farther from the substation. The schematic diagram of voltage profile is shown in Fig. 1.10.

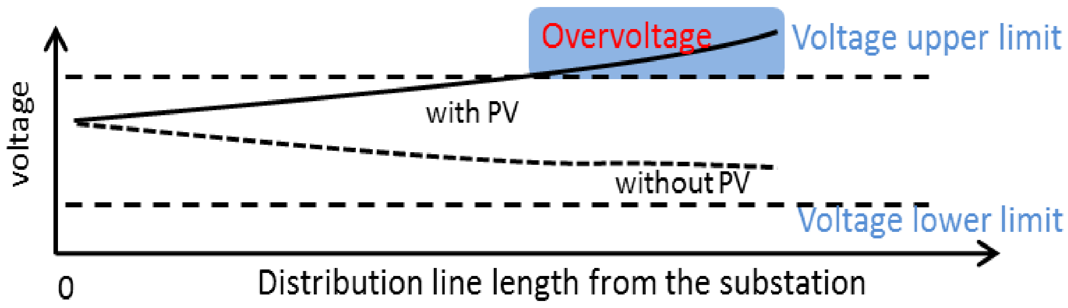

Fig. 1.10 Schematic diagram of overvoltage

In some distribution systems, PV generation should disconnect to the grid or reduce electricity output when overvoltage occurs at its node. The owners of PV systems at these farther location nodes have higher possibility of suffering from overvoltage and are thus required to reduce their PV generation output. As a result, it becomes unfair for PV owners to derive the FIT benefit from selling surplus power.

1.2.3 Low voltage problem

When large amount of EVs are charging at the same time, the distribution line current becomes large. According to equation (1-1) and (1-2), the voltage drop of the distribution line ΔV_{c1}, ΔV_{c2} becomes large in Fig. 1.9. At this time, V_1 is greater than V_2, and the approximate values are expressed by (1-5) and (1-6). If the electricity consumption keeps on increasing, the customer 2 will first suffer from low voltage. In a distribution system, low voltage will happen more frequently at the location farther from the substation. The schematic diagram of low voltage is shown in Fig. 1.11.

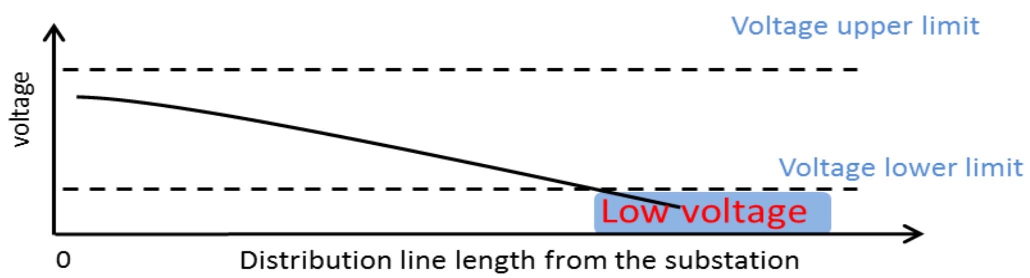

Fig. 1.11 Schematic diagram of low voltage

1.2.4 Existing voltage control methods

To solve the voltage violation problem, a series of studies has been performed. Researches on the operation and coordination of voltage control devices in distribution system such as on-load tap changer (OLTC), step voltage regulator (SVR), static var compensator (SVC), shunt capacitor (SC) and/or shunt reactor (SR), are basic approaches from the distribution system operator's (DSO's) aspect [33]–[41]. These researches aim to maintain the grid voltage within the allowed range as well as to relieve the mechanical switching-based devices operation stress. It is foreseeable that the control of voltage regulation devices would become more complicated, and more investment of regulation devices are needed in the future distribution system. Reactive power optimization methods are widely researched for voltage regulation in low voltage networks [42]–[48]. Approaches of actuating grid connected PV inverters to produce/absorb reactive power for overvoltage prevention are attracting more attention in recent years [45]–[48]. Due to the low X/R ratio in LV networks, the effect of reactive power is limited. Active power curtailment for PVs is also considered in [49], [50]. However, the key point of these methods is to decrease the active power output through the inverter, which leads to a decrease in solar energy utilization. Besides, utilization of an energy storage system (ESS) is considered to increase the penetration of PV in a distribution system [51]–[53]. Coordinated control of ESS with OLTC is proposed in [51] to solve the overvoltage problem with the main objective of decreasing the frequency of OLTC tap operation.

In recent years, application of demand side management (DSM) technique for voltage regulation has become attractive owing to its potential to more efficiently use available distributed energy resources [54]–[60]. Reference [54] proposes a reward-based demand response (DR) algorithm for residential customers to shave network peaks and improve voltage performance. A decentralized multi-agent system for the coordination of active power demand and plug-in electric vehicles is proposed in [55]. However, these studies do not consider the overvoltage problem caused by PV systems. Reference [56], [57] compares the centralized and local control methods of customer heat pump to mitigate voltage rise. The authors of [56], [57] only focuses on the heat pump as the controllable load, however, there are also other types of controllable loads such as air conditioner, rice cooker and so on. Reference [58] proposes an energy consumption scheduling algorithm, in which the deferrable loads are scheduled to jointly shave the peak load and reduce the reverse power flow. A price elasticity matrix based method [59] and a real-time decentralized DR control mechanism called grid explicit congestion notification (GECN) [60] are developed for the primary voltage control. These two methods use the price or GECN signal to modify the customer behavior of schedulable loads (SLs). For example, the GECN signal encourages customers to start using appliances to reduce the voltage. However, according to the current FIT program in Japan and other most of countries, only customer surplus power can be bought by the power company. As a result, customers would not be willing to shift their SLs to work at overvoltage period because it will reduce their surplus powers. Moreover, fairness problem arises when DR is implemented for voltage regulation. As pointed in [61], customers at the end of an LV feeder would be the main contributors to the voltage regulation. In other words, these customers can benefit more from DR. Hence, the overvoltage mitigation method at demand side should both consider the FIT profit and fairness among customers.

1.2.5 Voltage control via load scheduling

This research utilizes load scheduling method for voltage control in the distribution system. With the development of DSM, household loads can be scheduled by EMS for shaving peak power. Similarly, load scheduling can also be utilized for voltage control. For example, overvoltage can be mitigated by shifting the load to the period when PV output is large. To explain the method of overvoltage solution by load scheduling, a modified diagram of Fig. 1.10 with customer SLs is shown in Fig. 1.12, where the power of the SLs is denoted as P_{SL1} and P_{SL2}.

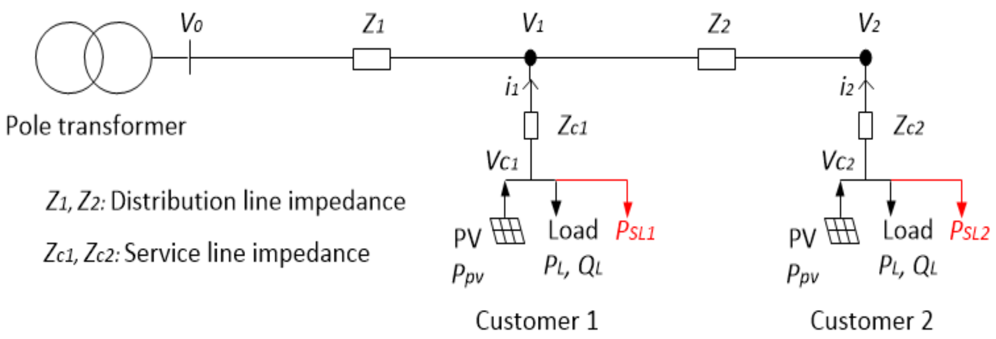

Fig. 1.12 Overvoltage solution by load scheduling

In this case, the approximate service line voltage drop is amended, as expressed by (1-7) and (1-8).

$$\Delta V_{c1} = -Z_{c1} i_1 \approx \frac{R(P_L + P_{SL1} - P_{PV}) + XQ}{|V_{c1}|} \tag{1-7}$$

$$\Delta V_{c2} = -Z_{c2} i_2 \approx \frac{R(P_L + P_{SL2} - P_{PV}) + XQ}{|V_{c2}|} \tag{1-8}$$

By injecting the SL power (i.e., P_{SL1} and P_{SL2}), the amplitude of the negative voltage drop can be regulated smaller; thus, overvoltage can be prevented. Because the power flow calculation is non-linear, determining how much P_{SL} can prevent an overvoltage is difficult. However, from the above equations, two rules can be considered in determining P_{SL}.

- If the objective is to decrease V_{c1}, starting the SLs at customer 1 can directly decrease the reverse current of the service line. In other words, the negative voltage drop at the service line of customer 1 can be more effectively decreased.
- From (1-8), starting SLs at the farther location of customer 2 can decrease i_2 and decrease V_{c2}, V_2, and V_1. Finally, V_{c1} in (1-3) can also be decreased.

In case an overvoltage is anticipated, starting the customer SLs can prevent the overvoltage. It is not needed to make all customers deliver the same SL capacity for the voltage regulation; however, an optimal combination should be searched. The above two rules are referred to in the optimization of determining the minimum capacity for overvoltage prevention. In this manner, the PV power can be fully utilized, and the whole customer community can obtain the maximum profit. Meanwhile, if the total profit can be allocated to customers with a proper policy, customers at different locations retain equal rights to generate profit from selling electricity and equal obligation to perform voltage regulation.

The low voltage solution by load scheduling is similar as overvoltage solution. In case a low voltage is anticipated, stopping and rescheduling a minimum capacity of loads can prevent the low voltage.

1.3 Research purpose and content

1.3.1 Research purpose

The purpose of this research is to apply the load scheduling method for the voltage control in next generation distribution system. A day-ahead load scheduling method and a real-time load rescheduling method are proposed in this research. The objectives of both day-ahead and real-time methods are to 1) maximize customers' profit and 2) reduce the voltage violation frequency of the power distribution system.

1.3.2 Contributions of this research

The main contributions of this paper are summarized as follows:

1) This research paper proposes a central CEMS and multi-sub-CEMS structure in which all household SLs are utilized as the voltage control resource. It is assumed that the CEMS is owned by the electricity retailer belong to an electricity market. It is possible in next generation distribution system. Customers SLs are managed by the

CEMS with the purpose of maximizing profit and helping the DSO with the voltage regulation.

2) A day-ahead load scheduling method is proposed. The main objective of day-ahead scheduling is to optimally schedule the working time of SLs according to the day-ahead electricity price, and simultaneously reduce the voltage violation frequency. The scheduling is performed by each sub-CEMS, and is solved by genetic algorithm (GA).

3) A coordinated real-time load rescheduling method is proposed. Voltage control of an OLTC and CEMS is also proposed. The main objectives of this control are to relieve the stress in the OLTC tap operation using the SLs and to follow the day-ahead schedule. The scheduling performed by each sub-CEMS is formulated as a combinatorial nonlinear scheduling optimization problem, which is solved by a sequential search method named voltage ranking-based load combination search algorithm (VRLCS).

4) The effectiveness of the proposed coordinated control is validated in a 1800-customer distribution system model. Some comparison cases are considered to show the effectiveness of the proposed method.

1.3.3 Organization of chapters

This dissertation consists of five chapters, and the contents are summarized as follows:

Chapter 1 describes the research background. Development of the next generation distribution system is introduced. The voltage violation problems are also introduced in this chapter.

Chapter 2 describes the household load model and the proposed central CEMS and multi-sub-CEMS model in the distribution system. These models are the base of the voltage control methods in this research.

Chapter 3 introduces the day-ahead load scheduling method. The purpose of this method is to maximize customers’ profit and reduce the distribution system voltage violation frequency. The problem is formulated as an optimization problem, and GA is applied to solve the optimization. The proposed method is first simulated on a 12-customer small distribution system and then on a 1800-customer large normal Japanese distribution system.

Chapter 4 introduces the real-time load rescheduling method. In this chapter, a coordinated real-time voltage control of an OLTC and CEMS is proposed. The main objectives of this control are to relieve the stress in the OLTC tap operation using the SLs and to follow the day-ahead schedule as much as possible. The scheduling performed by each sub-CEMS is formulated as a combinatorial nonlinear scheduling optimization problem, which is solved by the VRLCS. Besides, reactive power generated by PV inverter is also applied in the overvoltage regulation. At last, the equivalent SVC capacity is calculated to evaluate the voltage regulation function of the proposed load scheduling method.

Chapter 5 presents the conclusion of this dissertation.

Chapter 2 Proposed System Model

This chapter introduces the system model of this research. With the development of HEMS and CEMS, smart household appliances can be automatically scheduled to manage the energy consumption more efficiently. The load model is introduced in section 2.1, HEMS and CEMS function are introduced in section 2.2. The central CEMS and multi-sub-CEMS structure are introduced in section 2.3. With the electricity liberation, the power distribution system is changing significantly. The duty of DSO will focus on the power electricity quality management, and the electricity trading will be carried out by electricity retail companies. Section 2.4 introduces the model of the whole power distribution system and specifies the duty of each composition.

2.1 Household load model

In this study, the household loads are classified into two categories: on-demand loads (ODLs) and schedulable loads (SLs), which are denoted by l^{odl} and l^{sl}, respectively. The ODLs refer to those appliances that only work when the customer turns them on, such as light, computer, television and so on. The energy consumption of these loads cannot be shifted, so they are difficult to be controlled by the CEMS for voltage regulation. By contrast, the working time of SLs can be arranged flexibly and automatically operated by the HEMS, such as air conditioner, washing machine, rice cooker and so on. Therefore these SLs can be easily utilized for voltage regulation. Furthermore, the SLs are further divided into interruptible and non-interruptible ones. An air conditioner is a typical interruptible load, which can be interrupted frequently during its operation, while a rice cooker is a typical non-interruptible load, which cannot be stopped during its operation time.

An SL usually can be work during a time period but not a specific time point. For example, a washing machine can ever work in the night or day time; the important thing is that it should finish its working during the customer desired time period. Because of this flexibility, the scheduling of SLs can be utilized for peak power shaving and voltage control through EMS in the next generation distribution system. Residential consumer can set an allowed working period in advance, and then let the EMS to manage the operation of the appliance. For this structure, load scheduling method can be realized and it can be both beneficial for customers and distribution system.

Residential houses may have several SLs, which is denoted by $A_i \epsilon l^{sl}$, where i is the appliance index number. The specifications of an SL, which are required for the operation in this paper, are as follows:

- Rated power P_{A_i} [kW].
- Interruptible index INR_{A_i}, which indicates whether the SL is interruptible or not.
- Operation time $T_{A_i}^{ot}$, which means appliance A_i needs $T_{A_i}^{ot}$ time spans to finish its work.
- Allowed working interval $[\alpha_{A_i}, \beta_{A_i}]$.

The allowed working interval indicates that customers desired working period of appliance A_i. Hence, to ensure sufficient working time, appliance A_i must start working before $\beta_{A_i} - T_{A_i}^{ot}$. Therefore, time span $\alpha_{A_i} - \beta_{A_i}$ is greater than operation time $T_{A_i}^{ot}$. When it is equal to operation time $T_{A_i}^{ot}$, appliance A_i should work only within this fixed time interval and becomes non-schedulable. When this time span is greater than operation time $T_{A_i}^{ot}$, the starting time of appliance A_i can be chosen from α_{A_i} to $\beta_{A_i} - T_{A_i}^{ot}$. In this proposed system model, customers maintain their own control of household load usage and retain comfort by specifying their load usage.

2.2 Integrating the HEMS to the CEMS

In recent years, HEMS has been widely researched. In most HEMS, the SLs are shifted to the time period with the lowest electricity price in order to save electricity expense from the customer side perspective and to improve the peak-to-average ratio from the electricity supplier perspective [62]. Because the value of X/R in power distribution system is very small, active power adjustment becomes important in voltage control. As a result, the load scheduling method can also be utilized for voltage control.

Two typical structures of HEMS, called "individual customer interaction" and "all-customer interaction," are summarized in [63]. In the individual customer interaction, the HEMSs individually respond to the real-time price without any interactions with the other customers or HEMS behavior. This structure is easy to implement; however, it is difficult to apply to voltage control. The reason is that the voltage profile along the feeder is a result of all customer actions. In the all-customer interaction structure, all customers in a certain area exchange their energy consumption schedules and repeatedly revise them to achieve a global optimum. According to this structure, voltage regulation can be achieved. However, the communication framework is complicated, and the iteration for the global optimization may be time-consuming; thus, it is difficult to apply in real-time voltage control. It is pointed in the paper [58] that the hardware of HEMS should be powerful to realize the on-line optimization, and the current smart meter is not able to finish the optimization. The authors of [58] advise to utilize the cloud computing concept in the future.

Therefore, this paper utilizes CEMS structure to apply load scheduling for voltage control in distribution system. Referring to cloud computing concept, the CEMS can be seen as a center server or a computing center, which collects information from customers' HEMSs, and then make the decision for all HEMSs. Under this structure, the computing function at the customers HEMSs is not needed, and HEMS is designed as a user interface to communicate and receive the operation signal from the CEMS. In other words, the control function of HEMSs is integrated to the CEMS. The most important points in the CEMS structure are consideration of the customer preference and privacy protection. As mentioned earlier, customers can individually specify their loads according to their lifestyle or personal preference. As a result, customers still retain control of their appliances. The function of the proposed structure is similar to the distributed HEMS. In the proposed structure, direct interactions among customers are not needed, and all information is only collected by the CEMS; thus, the privacy policy is ensured in the same degree as that in the distributed HEMS.

2.3 Multi-sub-CEMS structure

Usually, a power distribution system includes thousands of customers. The load scheduling includes power flow calculation, which is non-linear. As a result, it is difficult for a CEMS to finish the optimization for the whole system, and also difficult to be applied for real-time operation. This research divided the distribution system into multi-sub-CEMS structure. A sub-CEMS is an integration of the HEMS installed in the customers connected to the same pole transformer, because the customer voltages under the same pole transformer are high correlated. Fig. 2.1 presents the image of bi-directional communications between the individual customer HEMS and the sub-CEMS.

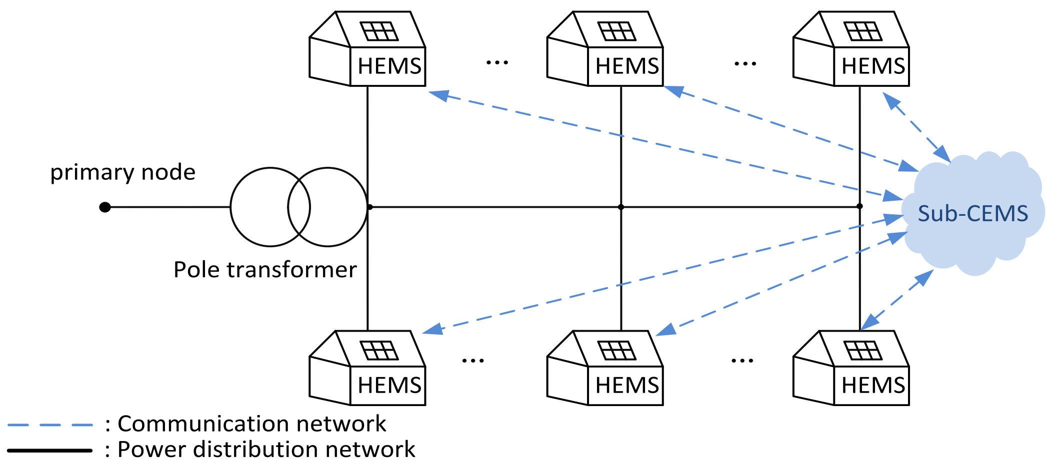

Fig. 2.1 sub-CEMS model

With the proposed sub-CEMS structure, customers load scheduling for the function of saving expense and voltage control can be realized. The detailed procedure of the interaction between the HEMSs and the sub-CEMS is described as follows:

- In day-ahead scheduling period:
  1) The customers set their SL specifications in their own HEMS, and the data are sent to the sub-CEMS in advance.
  2) The sub-CEMS estimates the ODL output according to customers' historical data and the PV output according to the weather report of the next day.
  3) With the day-ahead electricity price, CEMS makes the optimal schedule of the SL with the purpose of maximizing customers' profit and reducing the voltage violation frequency.
- In real-time operation period:
  4) HEMS sends its load consumption and PV output data to the sub-CEMS in real-time. The sub-CEMS aggregates the net load data and calculates the node voltage profile of its covering system.
  5) When overvoltage is anticipated, sub-CEMS decides the minimum capacity of the available un-started SLs to resolve the overvoltage. When low voltage is anticipated, sub-CEMS stops the minimum capacity of the working SLs and delays their working time to resolve the low voltage.
  6) Sub-CEMS sends the real-time load control signals to all HEMSs under its own covering system, and the individual HEMSs control their own SLs following the sub-CEMS instruction.

Because the power flow is a result of all customer actions of the whole power distribution system, this research assumes that a central CEMS is the main controller of the multi-sub-CEMS. The structure of central CEMS and multi-sub-CEMS is shown in Fig. 2.2.

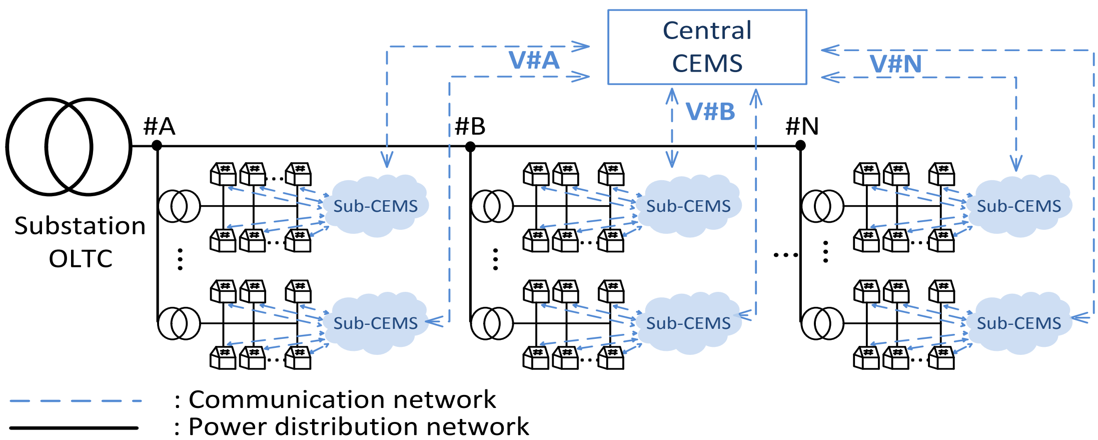

Fig. 2.2 Multi-sub-CEMSs model

This research assumes that the distribution feeder voltage profile management is organized as shown in Fig. 2.2. Central CEMS is on the top level and customers' HEMSs are on the bottom level. Central CEMS is the main controller, which communicates with the sub-CEMS. Sub-CEMS is the integration of the HEMS under the same pole transformer, which communicates with its covering HEMSs and makes the optimization. The primary function of the central CEMS is to induce the coordination among the multiple sub-CEMSs with the following procedure. First, each sub-CEMS collects the aggregated net load data of its covering sub-system and sends them to the Central CEMS. According to the data from the sub-CEMSs, the central CEMS calculates the voltage profile along the primary feeders and announces them to each sub-CEMS. By setting the announced voltage as the reference voltage, each sub-CEMS estimates the voltage profile in its coverage area and individually determines the adequate load schedule. With this multi-agent based structure, each sub-CEMS can independently and concurrently manage the cooperative real-time voltage violation prevention. Therefore, the proposed method can be applied to any distribution network by dividing the system into appropriate number of sub-CEMSs.

2.4 Assumed distribution system model

Based on the above mentioned central CEMS and multi-sub-CEMS structure, the next generation distribution system model is shown in Fig. 2.3. As shown in the figure, the system is mainly combined with DSO, retailer (central CEMS & sub-CEMSs), and electricity market.

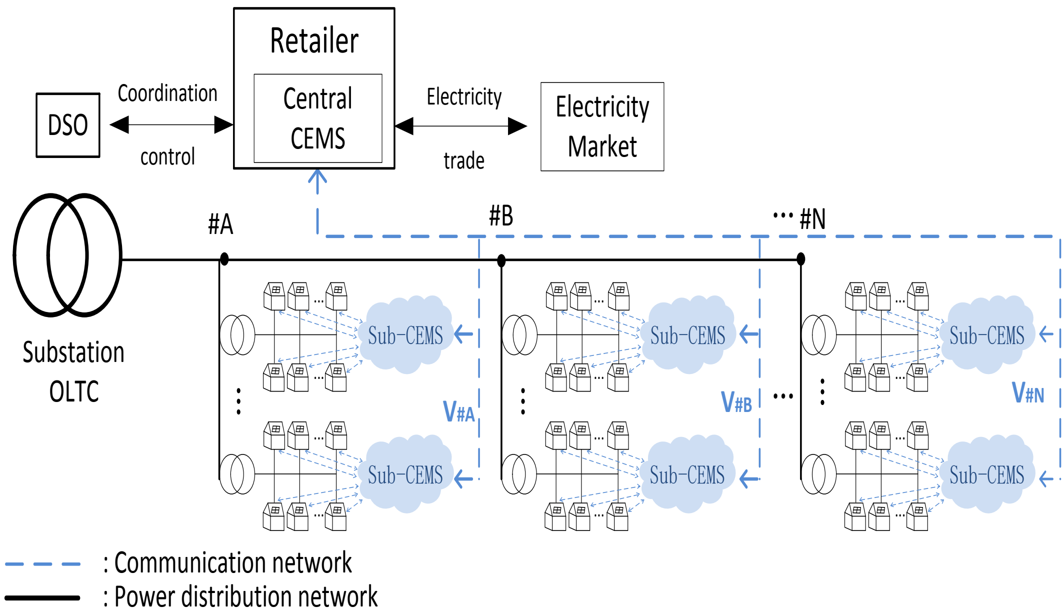

Fig. 2.3 Next generation distribution system model

The functions of these faculties are as follows:

1) DSO

In current Japan, the DSO is the operator and management of power distribution system, which not only ensures the electricity quality and also manages the electricity trading. With the process of electricity liberalization, the electricity will be sold by variety of power retailer companies to the end users. The main task of DSO will become to ensure the electricity quality.

In this research, the DSO is the main administrator of the distribution system, which controls and coordinates the voltage regulation resources, that is, OLTC and SLs directly and indirectly. Note that the major aim of this study is to apply a household load scheduling method for voltage regulation, and therefore, other typical voltage regulation devices such as SVR, SVC, SC and SR are not included from the scope of this study. The OLTC tap operation is conducted by the DSO when any sub-CEMS cannot solve the voltage violation.

2) Electricity market

The electricity market in this paper refers to the wholesale electricity market, which offer day-ahead electricity price to the retailer companies. The retailers then re-price the electricity and sell to the end consumers. According to the roadmap of Japan electricity market reform, the day-ahead and intraday electricity market is constructing in the period of 2016-2018 [64]. This paper takes the model of Nord Pool electricity market in north Europe and refers the day-ahead electricity price of Denmark.

3) Electricity Retailer

After the electricity liberalization, retailers will purchase electricity from the wholesale market and then sell to the end users. Furthermore, retailers can provide additional services to customers in order to both meet customers' requirements and better manage retailer's energy resources. For example, the ComEd Company in the US has already provided to end user a service called "Central Air Conditioning Cycling". If customers enroll this program, the ComEd will reduce customers' electricity demand on the hottest days of the summer by operating customers' compressor remotely but not affect customers' convenience [65]. By this program, customers can earn credits on their summer electric bill, and the ComEd company can also cut the peak power to manage its energy resources.

This research assumes that retailer is the owner of the CEMS. The basic function of the retailer is to purchase electricity from the electricity market and sell the surplus power from customers' side to the electricity market. The CEMS is an additional function, which help customers with the SLs schedule in order to maximize customers' profit and also help DSO to reduce voltage violation frequency.

4) Central CEMS & sub-CEMS

As mentioned in section 2.3, a large power distribution system can be divided into multi-sub-CEMS. A sub-CEMS is the integration of customers' HEMSs under the same pole transformer because the voltage of these customer nodes has high correlation. The function of the sub-CEMS is to optimize customers SLs scheduling with the purpose of saving electricity expense and helping the DSO to reduce the voltage regulation frequency. The functions of central CEMS are: 1) to communicate with sub-CEMSs and collect the load schedule from sub-CEMSs; 2) to realize the coordination control with DSO; 3) to make the electricity trading with electricity market.

5) Customers

In the assumed structure, customers can set some of their household loads as SLs, and then let the CEMS to optimally manage the working schedule. With the optimization carried by CEMS, customer can save their electricity expense, the DSO can release their voltage control stress, and the retailer can also get profit from the voltage regulation and electricity trading. In additional, as mentioned in section 2.1, customers maintain their own control of household load usage and retain comfort by specifying their SLs working period.

Chapter 3 Day-ahead Load Scheduling via CEMS

Many of the electricity markets offer the day-ahead price and real-time price (or intraday price) to the customers. Usually the day-ahead price is cheaper than the real-time price. Customers can schedule their SLs working at the low price period to save the electricity expense. Furthermore, because the feed-in tariff (FIT) for rooftop PV is counted by the surplus power, sub-CEMSs can optimally set the SLs schedule to produce more surplus power, so that the customers can earn more profit. However, from the DSO's perspective, this situation would increase difficulties in distribution system voltage control. For example, when large amount of EVs are charging at the same time of low price period, the voltage may fall below the low limit. In addition, when all customers are maximizing the surplus power when PV output is large, overvoltage problem may happen seriously.

The purpose of this research is to maximize customers' profit and simultaneously decrease the voltage violation number of times. This chapter introduces the day-ahead load scheduling method. At first, day-ahead scheduling in a sub-CEMS is proposed, and then the method is applied to a large distribution system with multi sub-CEMSs.

3.1 Day-ahead load scheduling in a sub-CEMS

3.1.1 Problem formulation

As mentioned in chapter 2, the customers' HEMSs will send the SLs specifications to the sub-CEMS. The sub-CEMS then optimally schedule the working time of SLs for profit maximization from the customers' perspective and reduce the voltage violation frequency from the DSO's perspective. The day-ahead scheduling is to decide the SLs starting time according to the day-ahead electricity price day before.

The day-ahead load scheduling of each sub-CEMS is formulated as an optimization problem with the objectives i) to maximize the profit of all the customers of its covering sub system, and ii) to minimize the voltage violation frequency. Sometimes load scheduling cannot avoid all of the voltage violation, so in day-ahead scheduling step, the objective is to make the voltage violation times as few as possible. For each sub-CEMS, the mathematical formulation is as follows:

$$Max \quad J = J1 - \alpha * J2 \tag{3-1}$$

$$J1 = \sum_{h=1}^{H} FIT_h - Charge_h \tag{3-2}$$

$$J2 = N_{vio} \tag{3-3}$$

$$FIT_h = C_{FIT} \cdot \frac{T}{60} \sum_{num=1}^{N_c} P_{surplus}^{num,h} \ , \ P_{surplus}^{num,h} > 0 \tag{3-4}$$

$$Charge_h = C_h \cdot \frac{T}{60} \sum_{num=1}^{N_c} P_{surplus}^{num,h} \tag{3-5}$$

$$P_{surplus}^{num,h} = P_{pv}^{num,h} + sign(EV) \cdot P_{EV}^{num,h} - P_{l^{odl}}^{num,h} - P_{l^{sl}}^{num,h} \tag{3-6}$$

$$sign(EV) = \begin{cases} -1, \ charge \\ 1, \ discharge \end{cases} \tag{3-7}$$

$$P_{l^{sl}}^{num,h} = \sum_{i=1}^{N_{A_i}} P_{A_i}^{num,h} \cdot SW_{A_i}^{num} \tag{3-8}$$

$$SW_{A_i}^{num} = \begin{cases} 1, \ A_i \ is \ on \\ 0, \ A_i \ is \ off \end{cases} \tag{3-9}$$

where FIT_h is the profit from FIT policy and $Charge_h$ is the electricity trading bill, and $\mathrm{N_{vio}}$ is the voltage violation number. In this research, the profit from FIT is the subsidy from the government, and the electricity selling and buying bill is calculated in the $Charge_h$. So in the objective function Eq. (3-1), *J1* indicates the financial part, and *J2* indicates the voltage violation number of times, and *α* is added to make the quantity of the two parts at the same order of magnitude. *h* identifies the time slot, *H* is the total time slot in a day, *T* is the time interval in every time slot [min], and *num* denotes the number of customers in the sub-CEMS. C_{FIT} and C_h are the FIT surplus power selling (customers sell to utility) price and day-ahead electricity trading price, respectively. $P_{surplus}^{num,h}$ indicates the surplus power, and $P_{pv}^{num,h}$ is the PV power, $P_{EV}^{num,h}$ is charging/discharging power, $P_{l^{odl}}^{num,h}$ is ODL power, and $P_{l^{sl}}^{num,h}$ is the SL power [kW]. The charging/discharging status of EV is indicated by $sign(EV)$. $P_{l^{sl}}^{num,h}$ is the summation of SLs power, and N_{A_i} is the number of SLs. $SW_{A_i}^{num}$ is the appliance switch, in which, 1 indicates that A_i is on and 0 indicates that A_i is off.

The constraints of the above mentioned optimization are as follows:

1) Equality constraints

- Nonlinear power flow equations:

$$V^{num,h}(I^{num,h})^* = P_{surplus}^{num,h} + jQ_{load}^{num,h} \tag{3-10}$$

2) Inequality constraints

- SLs specification constraint:

$$\alpha_{A_i} \le T_{A_i}^{start} \le \beta_{A_i} - T_{A_i}^{ot} \tag{3-11}$$

$$P_{A_i}^{h,num} = \begin{cases} P_{A_i},\ T_{A_i}^{start} \le h \le T_{A_i}^{start} + T_{A_i}^{ot} \\ 0,\ others \end{cases} \tag{3-12}$$

where, $V^{num,h}$ and $I^{num,h}$ are node voltage and line current, respectively. $Q_{load}^{num,h}$ is the load reactive power, while reactive power of PV is neglected in this step. $T_{A_i}^{start}$ is the starting time of A_i.

The direct decision value is $T_{A_i}^{start}$, and the variables such as $P_{l^{sl}}^{num,h}$, $P_{surplus}^{num,h}$ are decided by $T_{A_i}^{start}$. The variables such as $V^{num,h}$, N_{vio}, $\mathrm{Charge_h}$ and $\mathrm{FIT_h}$ are decided by $T_{A_i}^{start}$ and distribution model. In this research, GA is applied to solve the above mentioned optimization problem.

3.1.2 Optimization algorithm

3.1.2.1 Introduction of GA

GA is a metaheuristic inspired by the process of natural selection and evolution that belongs to the larger class of evolutionary algorithms. GAs are commonly used to generate high-quality solutions to optimization and search problems. The main processes for a GA are initialization, evaluation, selection, crossover, mutation, and iteration [66]–[68].

The first step of GA is initialization, in other words, to create an initial population. In GA, a chromosome is a solution for the optimization, and a set of chromosomes is called a population, which is usually randomly generated. The population can be any desired size, usually large size population can help the optimization to get a better result and consume longer calculation time.

After initialization is evaluation. Each chromosome of the population is then evaluated using a fitness function. The fitness function is used to measures the quality of solution, and usually is the objective function of the optimization problem. After that, chromosomes will be ranked with the fitness value, where solutions with high fitness are typically more likely to be selected.

The next step is selection. Selection helps the population evolution by discarding the bad designs and keeping the best individuals in the population. The basic principle of selection is to make it more likely that fitter individuals will be selected for the next generation. Especially, the best fitness chromosome will be kept directly to the next generation. There are some different selection algorithms, and one of the most common used algorithms is called roulette wheel algorithm. The name of roulette wheel is from a casino game, and the image is shown in Fig. 3.1 [69]. When the wheel is rotated, the selection point has higher possibility to stop at a larger proportion part of the wheel.

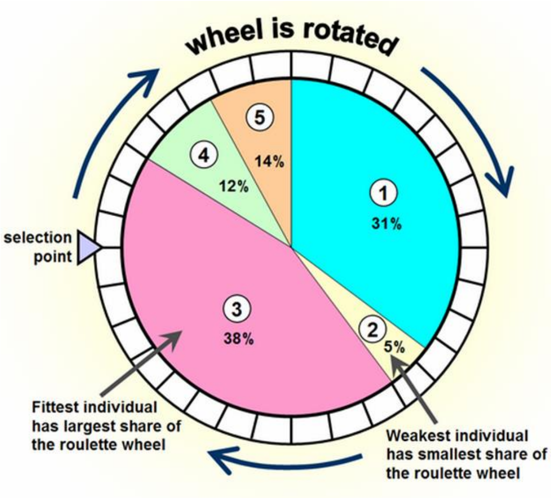

Fig. 3.1 Roulette wheel selection [69]

To apply the roulette wheel algorithm in the GA, a fitness percentage is used to indicate the proportion. If f_i is the fitness of chromosome *i* in the population, its probability of being selected is show in (3-13).

$$p_i = \frac{f_i}{\sum_{j=1}^{N} f_j} \tag{3-13}$$

where *N* is the total number of chromosomes in the population.

According to (3-13), the higher fitness chromosomes have higher possibility to be chosen in the selection, so the selection with roulette wheel algorithm is also called fitness proportionate selection.

After the selection is the step of crossover. During crossover, new chromosomes are created by combining the selected individuals, which is analogous to the reproduction and biological crossover. The hope is to generate a ‘fitter’ offspring which inherit the good gene from the parent chromosomes. There are many crossover techniques to form the new chromosomes and the most common used one is called single-point crossover. A single crossover point on both parents’ chromosomes is selected, and all data beyond that point in both chromosomes is exchanged between the two parent organisms. The resulting organisms are the children. The crossover process is shown in Fig. 3.2.

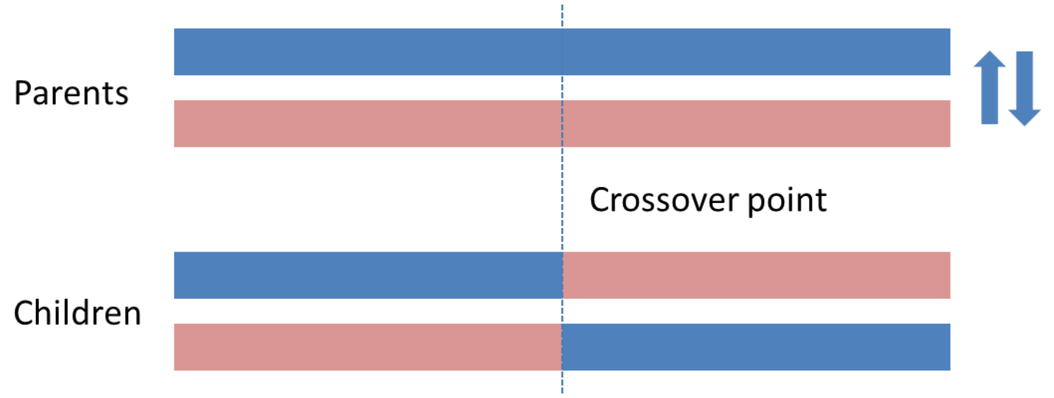

Fig. 3.2 Crossover process

Mutation happens in the generated children chromosomes after the crossover. It is mimicking to biological mutation, which will alters one or more gene values in a chromosome from its initial state (see Fig. 3.3). Mutation happens according to a user-defined mutation probability. By mutation, the solution may change largely from the previous one. Hence GA can come to better solution by using mutation. However, this probability is usually set as a low value. If it is set too large, the search will turn into a primitive random search.

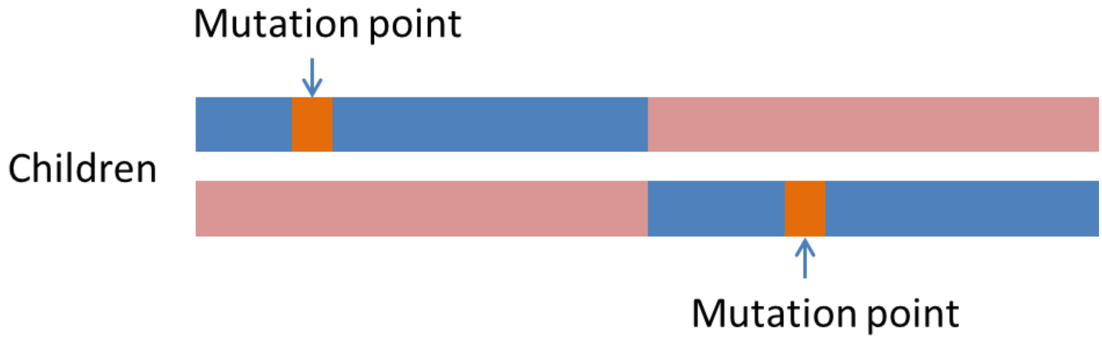

Fig. 3.3 Mutation process

After mutation, a new population is generated, and this population is called generation in GA. Usually the new population will be checked in specific optimization problem, and the new chromosomes violated the optimization constraints will be replaced by the one with best fitness value which is directly selected from the previous generation.

After that, GA repeats the process until get a pre-defined generation. Usually a GA process with larger population and longer generation will reach a better result; meanwhile, it will cost longer computation time.

3.1.2.2 Day-ahead load scheduling by GA

GA is applied to solve the optimization problem in section 3.1.1. In the optimization, the objective function of (3-1) is to maximize customers profit and minimize the voltage violation number of times. The decision value of the optimization is the starting time of customers SLs. The gene in each chromosome is the starting time of SLs which obeys the constraints of $T_{A_i}^{start} \in \left[\alpha_{A_i}, \beta_{A_i} - T_{A_i}^{ot} \right]$. As a result, the starting time of each SL will randomly generate and then formulate a chromosome in the initialization. After generated enough chromosomes, a population is built. The objective function of (3-1) is used for calculating the fitness function in the evaluation. A decoding process is included in the programming. The power of the SLs will be add to the time span according to the starting time (refer to equation (3-12) and (3-8)). After that, the electricity bill *J1*, and voltage violation condition can be calculated through the power flow calculation. Then the chromosomes are selected by the roulette wheel algorithm and a signal-point crossover is applied. In the mutation, a new randomly generated starting time $T_{A_i}^{start\prime}$ will replace the old one of the mutation point data. After that the GA finishes the process of one generation, and then repeats the process until reach the pre-defined generation. The whole process is shown in Fig. 3.4.

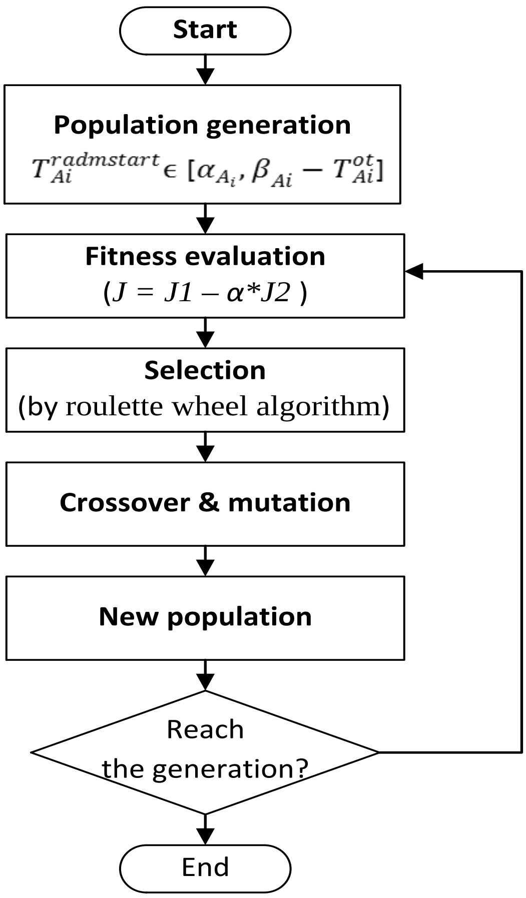

Fig. 3.4 GA optimization process

3.1.3 Simulation in a sub-CEMS on 2nd June, 2007

3.1.3.1 Simulation condition

As mentioned in section 2.3, a sub-CEMS is the customers under the same pole transformer. The performance of the GA optimization is first verified in a 12-customer distribution system model (see Fig. 3.5) [70]. A rooftop PV system and an EV are considered in all of the customers.

In this work, the assumed duration of the time slot is 15 min, i.e., a day has 96 time slots or $h \in [1, 96]$. In other words, the PV and ODL power is assumed unchanged within 15 min. The data of the PVs are referred from the demonstration project conducted by the New Energy and Industrial Technology Development Organization (NEDO) in Ota City, Japan. In this database, the data is recorded in every second. For the purpose of simulation, the data is transferred into 96 time slots by taking the average. 12 different profiles of PV and load are extracted from the database for the simulation of 12-customer system. The load data of each customer in the simulation includes two parts: one is the ODL and the other is the SL. Because it is incapable to divide the real load data into ODL and SL, the real residential load data of the above NEDO data is assumed as the ODL data. The SLs data is assumed from the daily used household appliances. Six most commonly used SLs are assumed as listed in Table 1, and the ones used for several times are marked with different numbers. All customer SLs are assumed identical for simplicity in this simulation.

The simulation is carried out on 2nd, June 2007. The 12 profiles of ODL and PV data are shown in Fig. 3.6 and Fig. 3.7, respectively. To perform a comparison, SLs starting at a random time point $T_{Ai}^{radmstart} \in [\alpha_{A_i}, \beta_{Ai} - T_{Ai}^{ot}]$ is assumed as the normal working period for these SLs. The average data of the 12 customers of the PV, ODL, and load power within running SLs at random time are shown in Fig. 3.8. For day-ahead load scheduling, estimation of PV and ODL data is needed. This research assumes that the data can be estimated relatively well with small error. The error is generated based on Gaussian distribution and the PV and ODL average data with error are shown in Fig. 3.9 and Fig. 3.10. The day-ahead electricity price is referred to the Denmark price of Nord Pool market on 2nd, June 2016 [71], and the data is shown in Fig. 3.11.

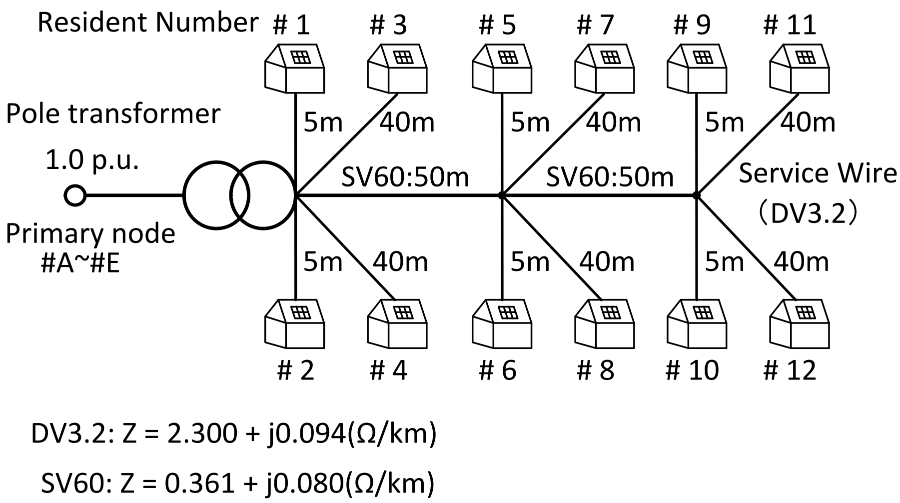

Fig. 3.5 A 12-customer distribution system model

Table 1 SL Specifications

A_i		$[\alpha_{Ai}, \beta_{Ai}]$	T_{Ai}^{ot} (min)	INR_{Ai}	P_{Ai} (kW)
1	Rice cooker	6:00-8:00	40	No	0.5
2	Ventilator	8:00-18:00	60	Yes	0.3
3	Washing machine	8:00-18:00	60	No	0.4
4	Air conditioner	9:00-12:00	60	Yes	1.5
5	Rice cooker	9:00-11:00	40	No	0.5
6	Air conditioner	12:00-15:00	60	Yes	1.5
7	Dish washer	13:00-16:00	40	No	0.6
8	Rice cooker	15:00-18:00	40	No	0.5
9	EV	18:00-6:00	360	Yes	3

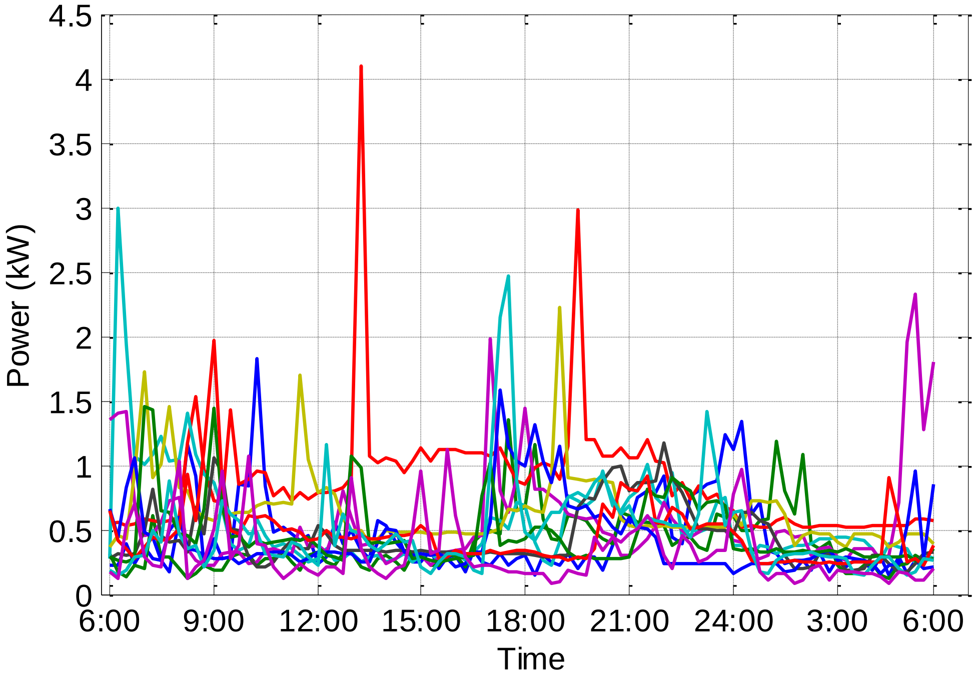

Fig. 3.6 Load profiles of 12 customers

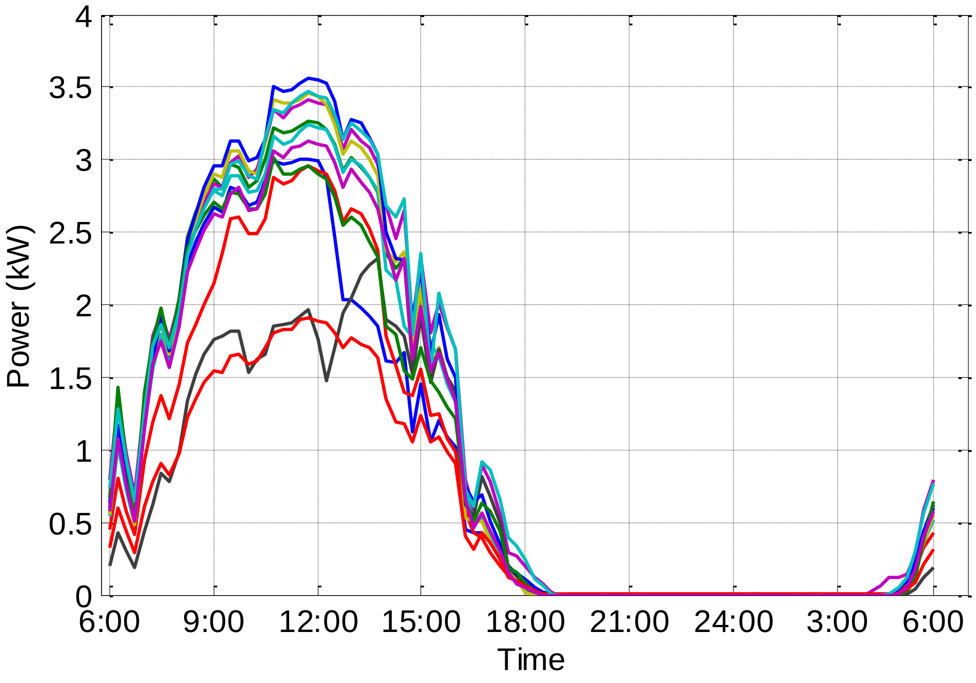

Fig. 3.7 PV profiles of 12 customers

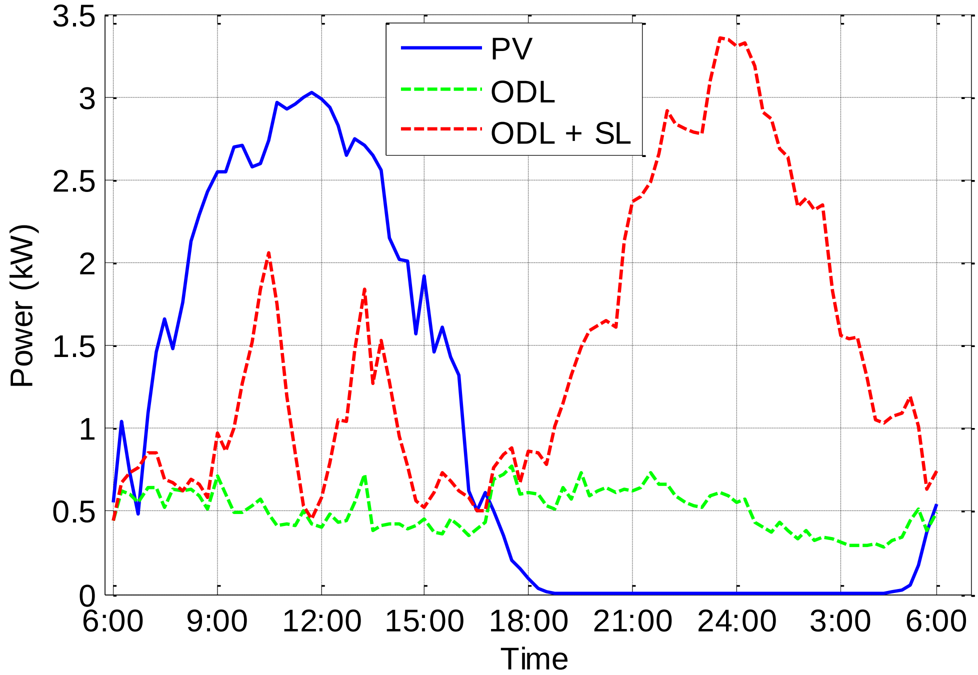

Fig. 3.8 Average PV and load power with running SLs at random time

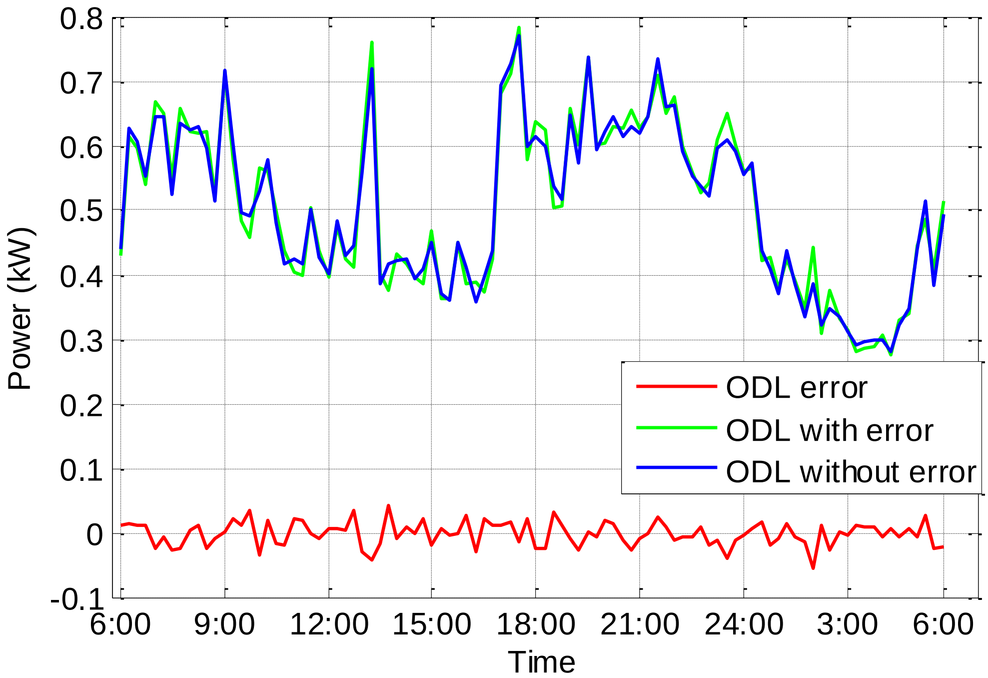

Fig. 3.9 Average ODL data and error

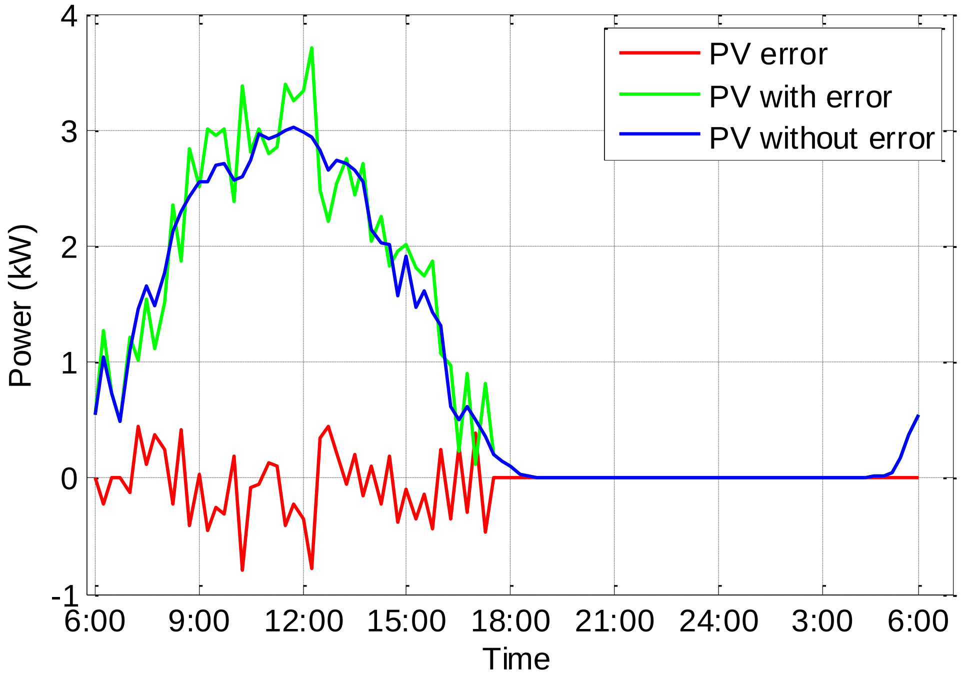

Fig. 3.10 Average PV data and error

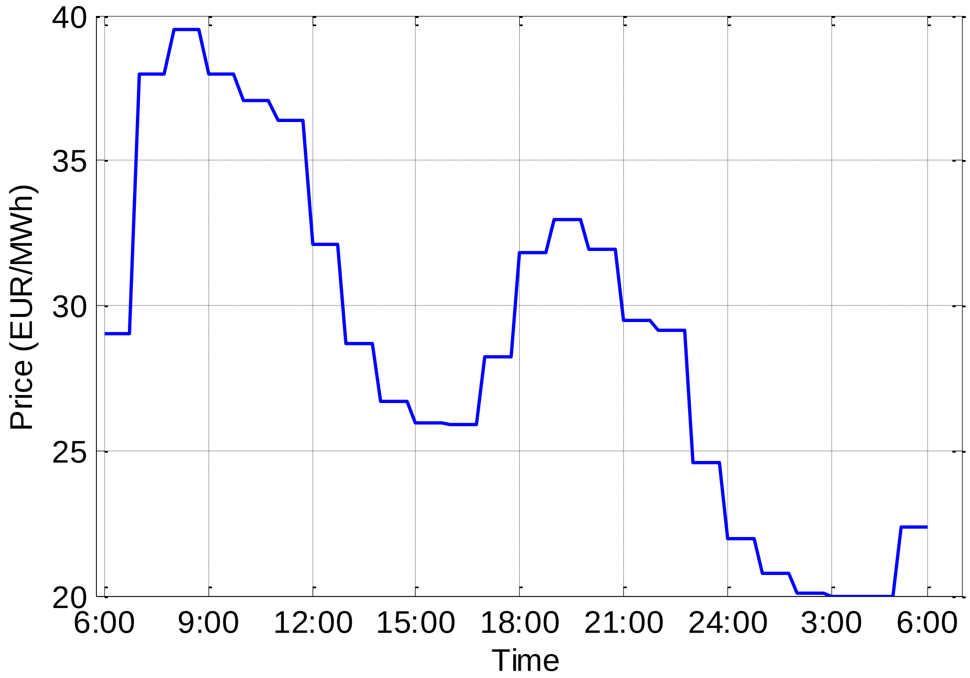

Fig. 3.11 Day-ahead price of 2016.6.2, Denmark

In Japan, the voltage at the customer end should be 101 ± 6 V. In this research, the overvoltage and low voltage point is set as 107 V and 95 V, respectively. The following three cases are considered in the simulation.

Case 1: no optimization. SLs are scheduled randomly.

Case 2: *Max J1* of equation (3-2)

Case 3: *Max J* of objective function (3-1).

For the three cases, the case 1 indicates that optimization is not applied. SLs are randomly scheduled in this case, which is the normal case that energy management system is not applied. In the case 2, only profit maximization is focused. In this case, if customers all schedule their SLs working at the low price period, their profit can be maximized but it may cause voltage violation in the system. In the case 3, proposed method is applied to consider both the profit maximization and voltage violation reduction.

In the simulation, the GA parameters are set and shown in Table 2. The sending voltage at pole transformer is set as 1.0 p.u..

Table 2 GA parameters

Population	20
Crossover rate	0.8
Mutation rate	0.02
GA iterations	5000

3.1.3.2 Simulation result

In the case 1, because optimization is not applied, the SLs starting time are randomly generated according to the constraint $T_{Ai}^{radmstart} \epsilon\ [\alpha_{A_i}, \beta_{Ai} - T_{Ai}^{ot}]$. GA is applied to solve the optimization problem in case 2 and case 3. The α in equation (3-1) is set as 10 to make the quantity of *J2* as similar as the *J1*. The convergence of GA calculation in case 2 and case 3 are shown in Fig. 3.12. The figures show that the optimization of GA in the two cases is converged after 4000 times of iteration. The simulation is carried out using MATLAB software in a typical personal computer with a CPU of Intel(R) Core(TM) i7-4770 @ 3.40GHz and 8 GB memory. The simulation time of the GA optimization is around 25 min for case 2 and case 3, which available for day-ahead optimization.

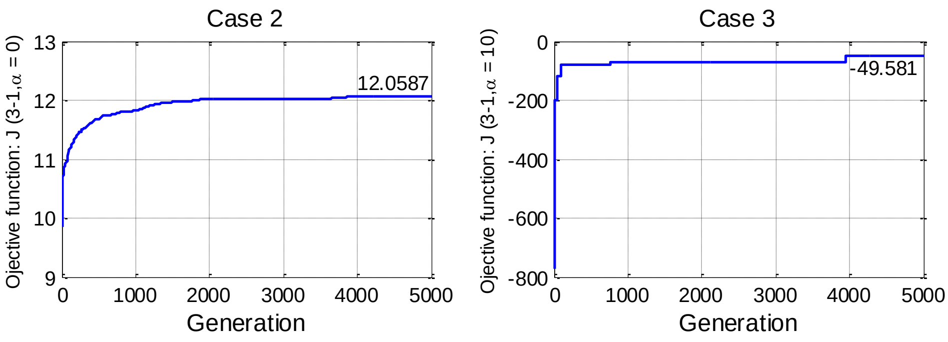

Fig. 3.12 GA iteration result of case 2 and case 3

In the objective function of (3-1), the part of *J2* is used in the fitness function of GA, for the purpose of reducing the voltage violation frequency as much as possible. So in the real profit calculation, the part of *J2* is not counted. The voltage violation times and the profit of the 3 cases are shown in Table 3. Here, the voltage violation number means that in case that one voltage violation (low voltage or overvoltage) happens in a customer, the voltage violation number will be added one.

Table 3 Simulation results of 3 cases

	Low voltage violation number	Overvoltage violation number	Profit (EUR)
Case 1	53	0	10.18
Case 2	73	0	11.88
Case 3	6	0	10.42

In case 1, there are 53 times low voltage violation of the 12 customers, while the violation number in case 2 and case 3 are 73 and 6 respectively. Case 2 achieves the max profit through the optimization because the optimization only focuses the profit and ignores the voltage condition. The voltage violation in case 2 is the most serious. Comparing case 1 and case 3, the profit of case 3 is better than case 1 and the voltage violations times of case 3 is less than case 1. The results show that the day-ahead optimization is effective for maximizing the profit while reducing the voltage violation times as few as possible. The 12-customer voltage condition of the day in 3 cases are shown in Fig. 3.13, Fig. 3.14 and Fig. 3.15.

The day-ahead price, average power of PV, SL and ODL of the 3 cases are shown in Fig. 3.16, Fig. 3.17 and Fig. 3.18. According to the assumption of SLs specifications in Table 1, EV is the only SL during the night and the allowed working time of EVs is from 18:00 to 6:00, so the average SL is a normal distribution in case 1 (see Fig. 3.16). Because the day-ahead electricity price is relative cheap during 24:00 to 6:00, the EVs are mostly scheduled to work during this time period in case 2 (see Fig. 3.17). As a result, low voltage violation occurs when most of EVs are charging at the same time. In case 3, the EVs are scheduled to not charge during the same time period in order to reduce the low voltage violation frequency, so the peak power during the night is much lower than in case 2 (see Fig. 3.18).

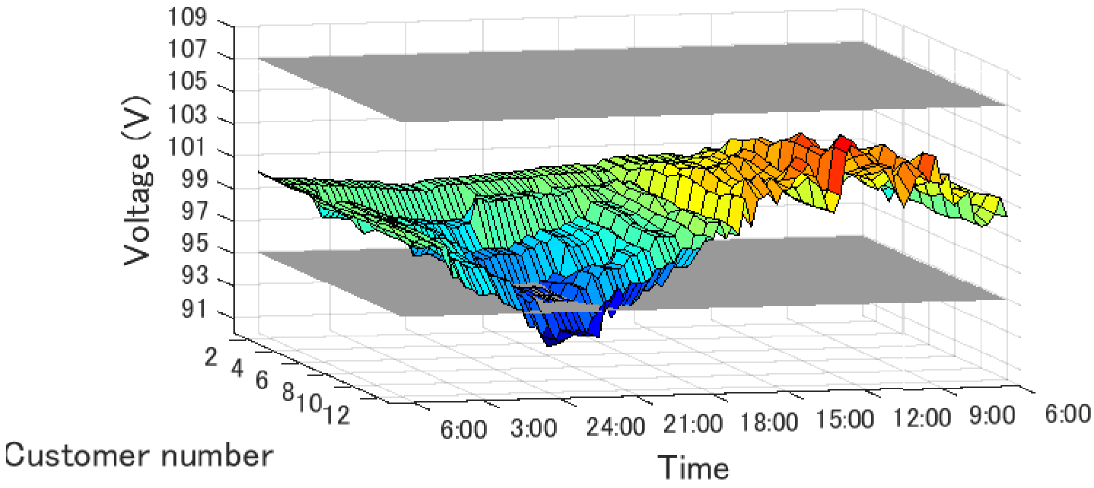

Fig. 3.13 12-customer voltage condition of case 1

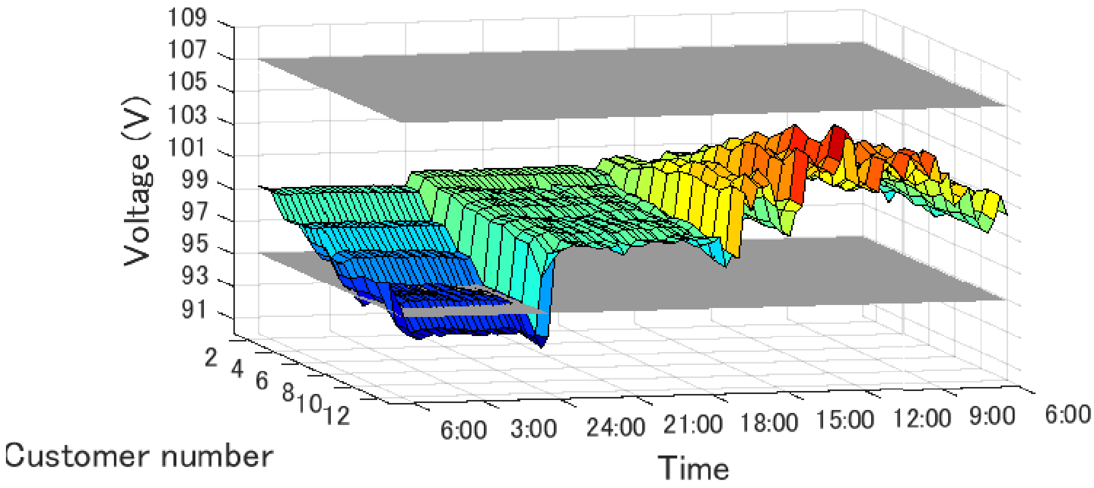

Fig. 3.14 12-customer voltage condition of case 2

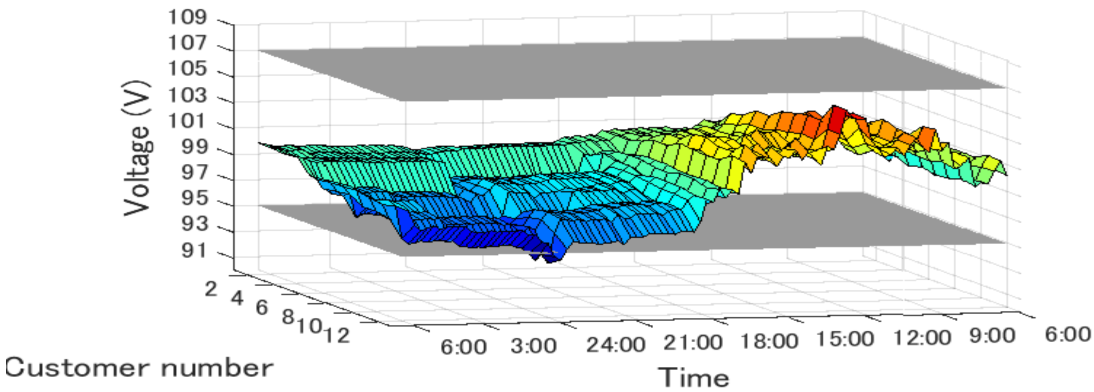

Fig. 3.15 12-customer voltage condition of case 3

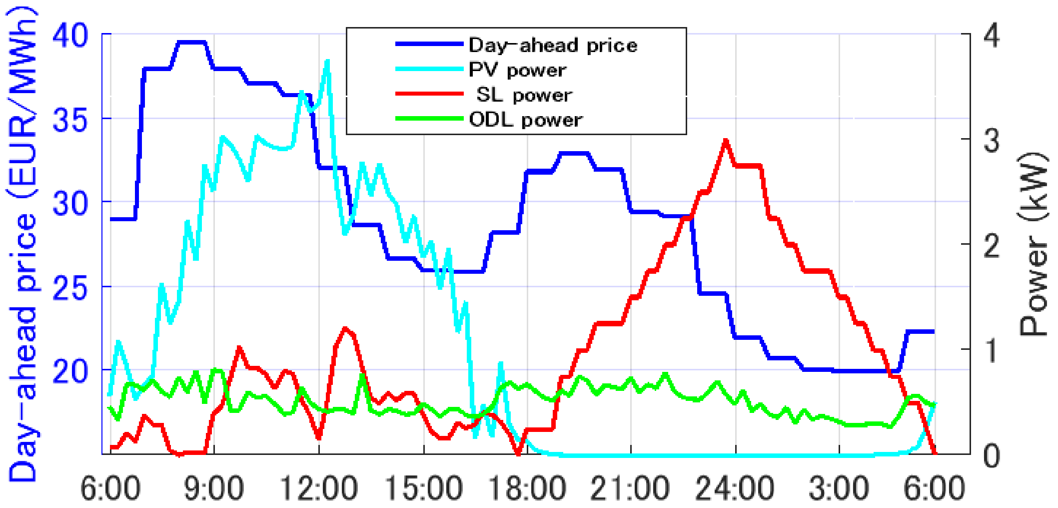

Fig. 3.16 Day-ahead price and PV, SL, ODL average power of case 1

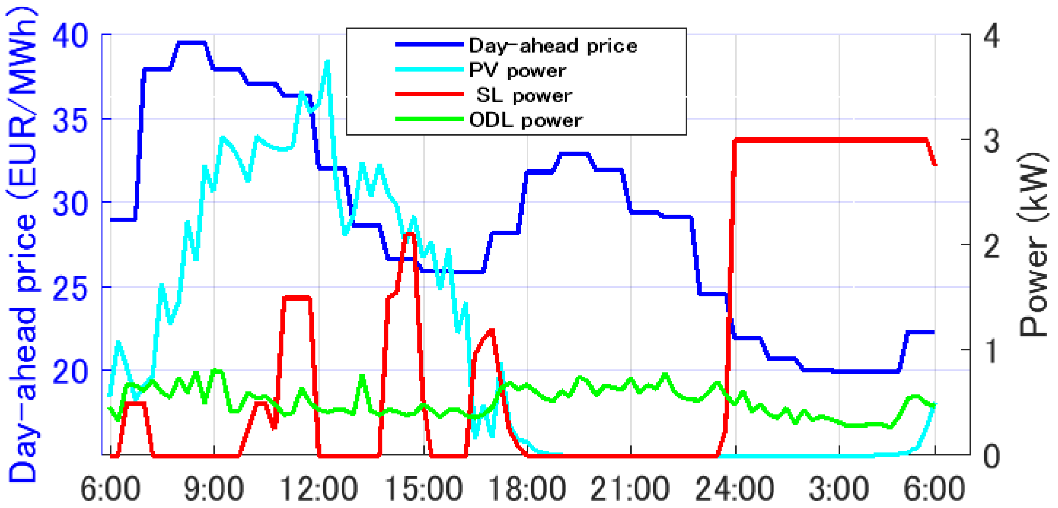

Fig. 3.17 Day-ahead price and PV, SL, ODL average power of case 2

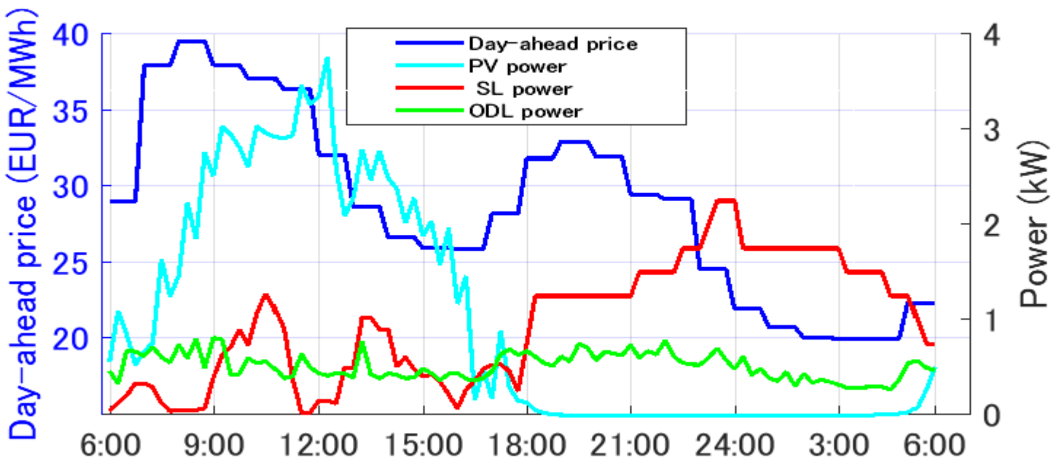

Fig. 3.18 Day-ahead price and PV, SL, ODL average power of case 3

3.2 Day-ahead scheduling in multi-sub-CEMSs

3.2.1 Optimization of multi-sub-CEMSs

As mentioned in section 2.3, a large distribution includes thousands of customers. The voltage-related optimization includes the non-linear power flow calculation, thus, it is difficult to solve the optimization with a single CEMS. Furthermore, a single CEMS structure is difficult to be applied for the real-time operation.

The research defines the central CEMS and multi-sub-CEMS structure. The sub-CEMS is the integration of customers under the same pole transformer, and the central CEMS is the main controller of the system with the function of coordinating all sub-CEMSs. Under this structure, each sub-CEMS finishes the above-mentioned day-ahead optimization separately and concurrently. However, a sub-CEMS cannot know the voltage information at its pole transformer, because power flow is the result of all customer actions. This research assumes that the central CEMS collects all the information of the distribution system. With the information, central CEMS can do the power flow calculation, and then announces the primary node voltage (voltage of at the pole transformer) to each sub-CEMS. In this way, the proposed method can be applied to any power distribution system by dividing the system into proper number of sub-CEMSs. The information interaction between central CEMS and multi-sub-CEMS is shown in Fig. 3.19

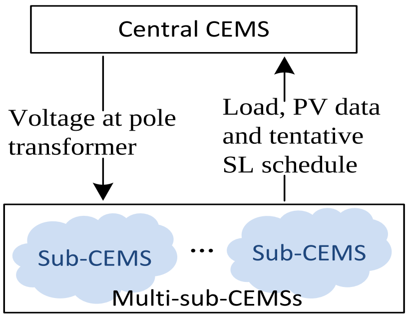

Fig. 3.19 Interaction between central CEMS and multi-sub-CEMS

3.2.2 Simulation in multi-sub-CEMSs on 2nd June, 2007

3.2.2.1 Simulation condition

The performance of the GA optimization of multi-sub-CEMS is verified in a 1800-customer distribution system model (see Fig. 3.20) [70]. The sending voltage of OLTC is set as 1.0 p.u.. All of the 1800 customers are installed with a rooftop PV system and an EV in the simulation.

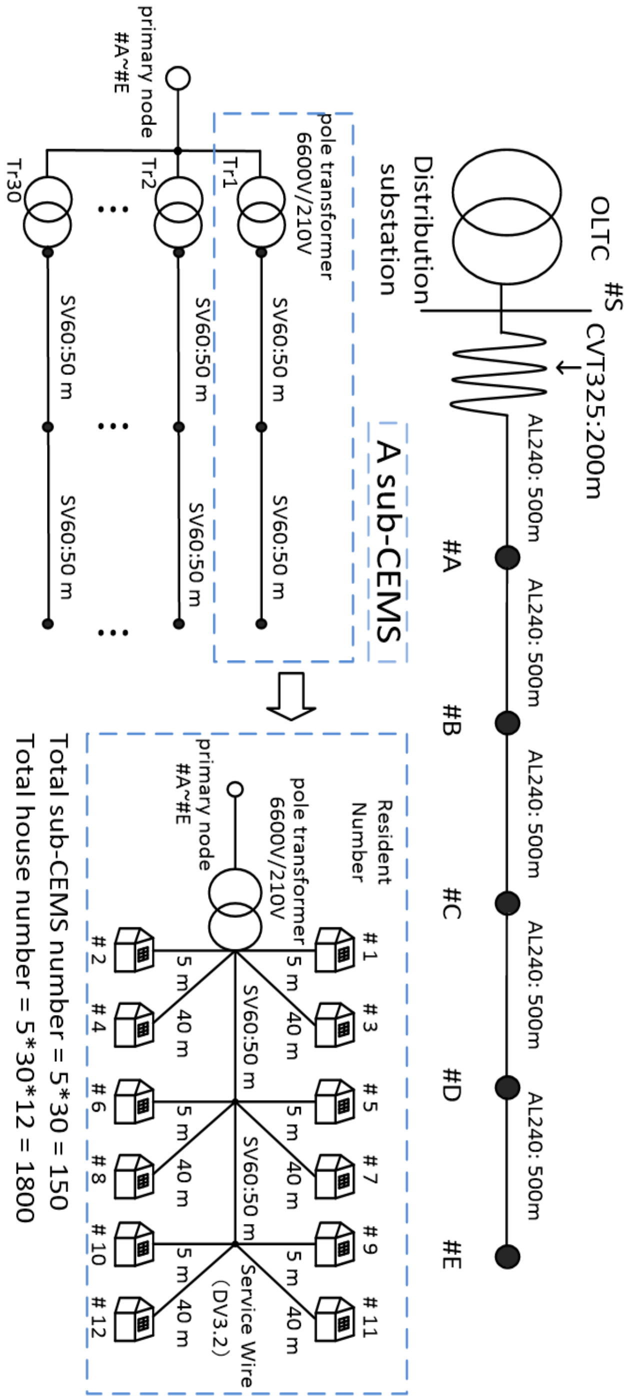

Fig. 3.20 1800-customer distribution system model

The system parameters are listed in Table 4.

Table 4 Distribution system parameters

	Resistance [Ω/km]	Reactance [Ω/km]	Capacitance [μF/km]
CVT325	0.0579	0.0951	0.305
AL240	0.124	0.311	0
SV60	0.304	0.0807	0
DV32	2.3	0.094	0
Pole transformer TR	8.314	14.271	0

The simulation duration of the time slot is 15 min, i.e., a day has 96 time slots or $h \in [1, 96]$. The data of the PVs are referred from the NEDO project in Ota City, Japan. 450 different profiles of PV are extracted from the database. Similarly, the ODL data is also referred to the 450 different profiles of real residential load data. These data are replicated four times and randomly assigned to the 1800 customers. The SL data is assumed same as Table 1 in section 3.1.3, and all customer SLs are assumed identical for the simplicity in the simulation.

In the multi-sub-CEMS structure, each sub-CEMS realizes the optimization separately and concurrently. Similar as section 3.1.3, three cases are considered in the simulation:

Case 1: no optimization. SLs are scheduled randomly.

Case 2: *Max J1* of equation (3-2)

Case 3: *Max J* of objective function (3-1).

3.2.2.2 Simulation result

The 1800-customer voltage condition of case 1, case 2 and case 3 on 2nd June are show in Fig. 3.21, Fig. 3.22 and Fig. 3.23, respectively.

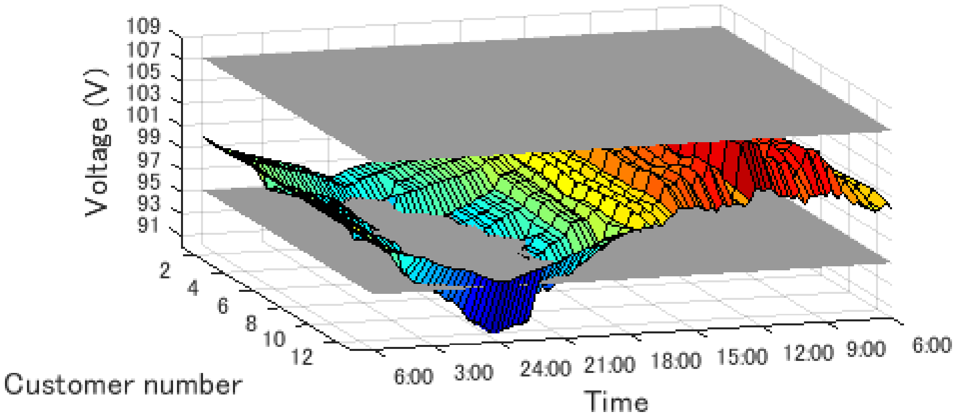

Fig. 3.21 1800-customer voltage condition of case 1 on 2nd June

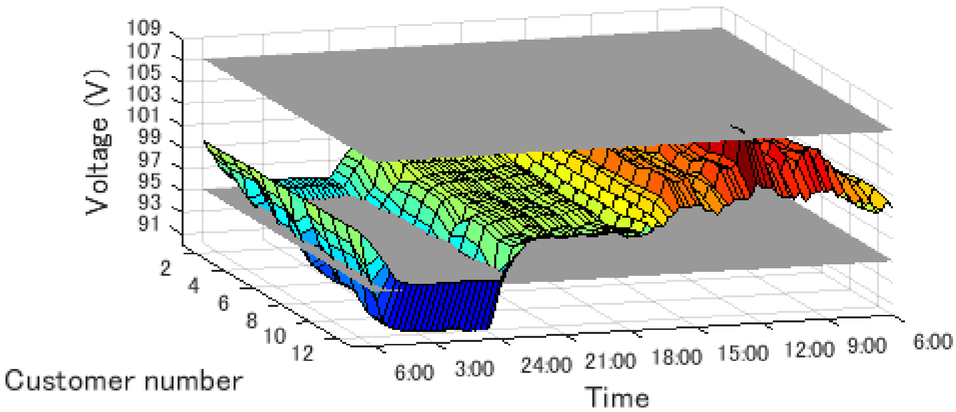

Fig. 3.22 1800-customer voltage condition of case 2 on 2nd June

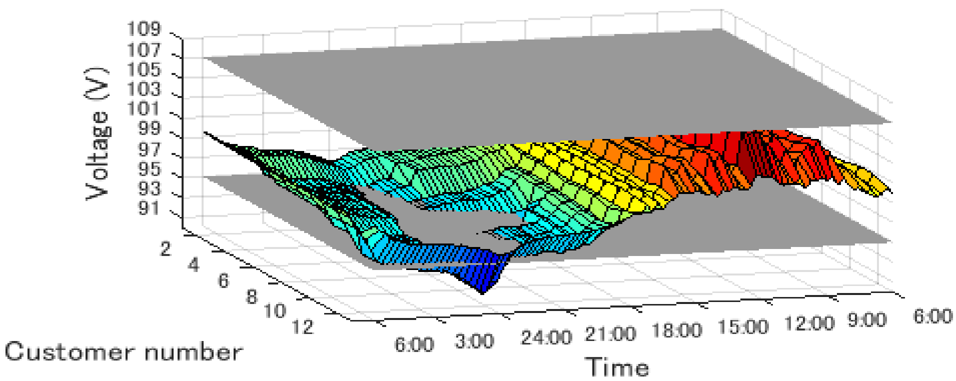

Fig. 3.23 1800-customer voltage condition of case 3 on 2nd June

The voltage violation times and the profit of 3 cases on 2nd Jun are shown in Table 5. Here, the voltage violation number means that in case that one voltage violation (low voltage or overvoltage) happens in a customer, the voltage violation number will be added one.

Table 5 Simulation results of 3 cases on 2nd Jun

	Low voltage violation number	Overvoltage violation number	Profit (EUR)
Case 1	24532	0	1247.2
Case 2	30438	20	1425.4
Case 3	19692	0	1263.8

Comparing to the result in section 3.1.3.2, the voltage violation number of times are much more than that in Table 3. One of the reasons is that the customer number increases. Another reason is because of the distribution line length increment. The voltage drop along the distribution line is increasing with the line length, so the voltage violation is much more serious than the 12-customer small system.

3.2.3 Simulation in multi-sub-CEMSs in 30 days

3.2.3.1 Simulation condition

The simulation is also carried out in a month period of June 2007. Among the 30 days, the PV peak power of the aggregated 1800 customers is 5.83 MW and the peak load is 4.11 MW. The 30 days average data of PV, ODL, and ODL with SLs working at random time is shown in Fig. 3.24. The day-ahead electricity price is referred to the Denmark price of Nord Pool market in June 2016 [71], and the data is shown in Fig. 3.25.

The sending voltage of OLTC is set as 1.0375 p.u. in this simulation, and the other simulation conditions are same as that in section 3.2.2.

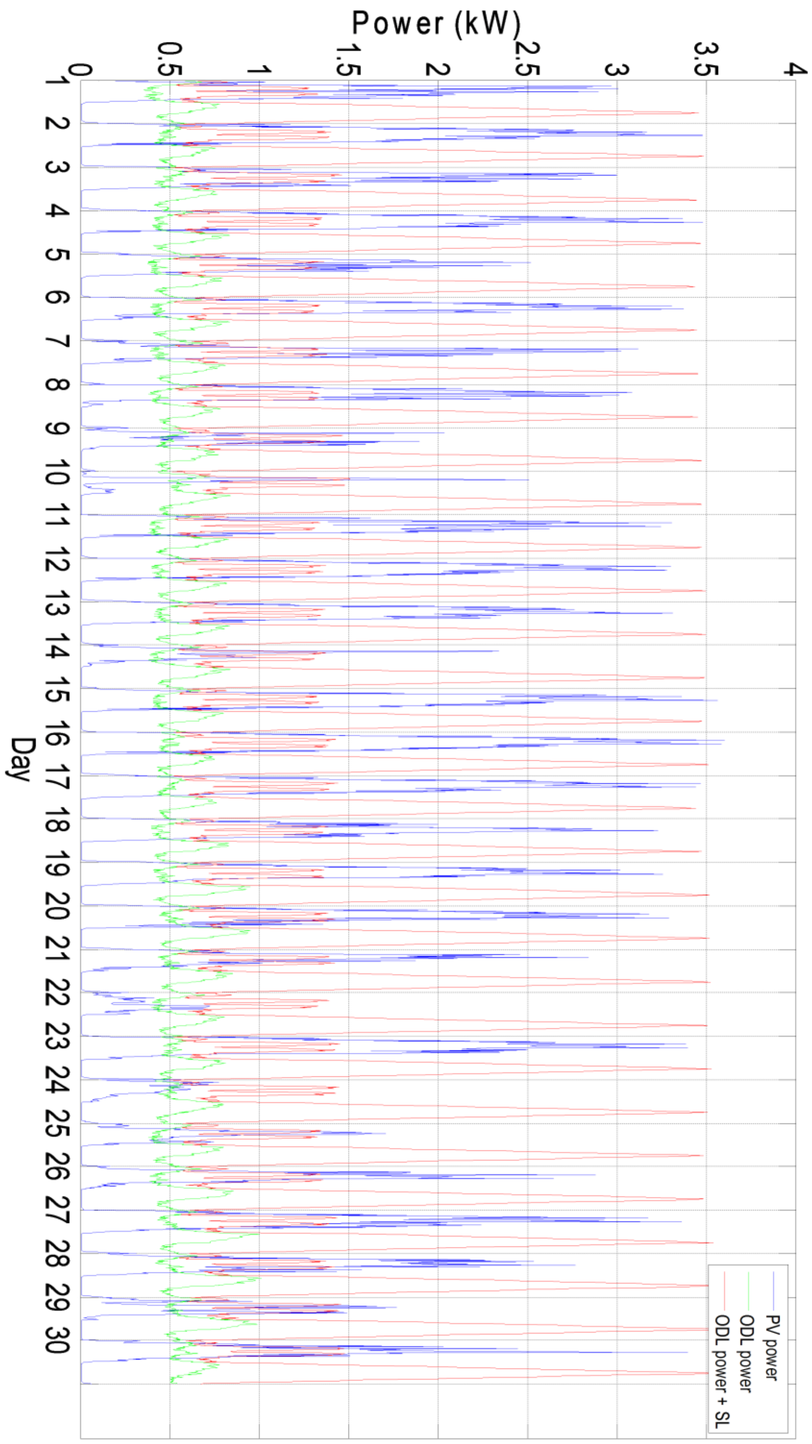

Fig. 3.24 Average data of PV, ODL, and ODL with SLs of 30 days

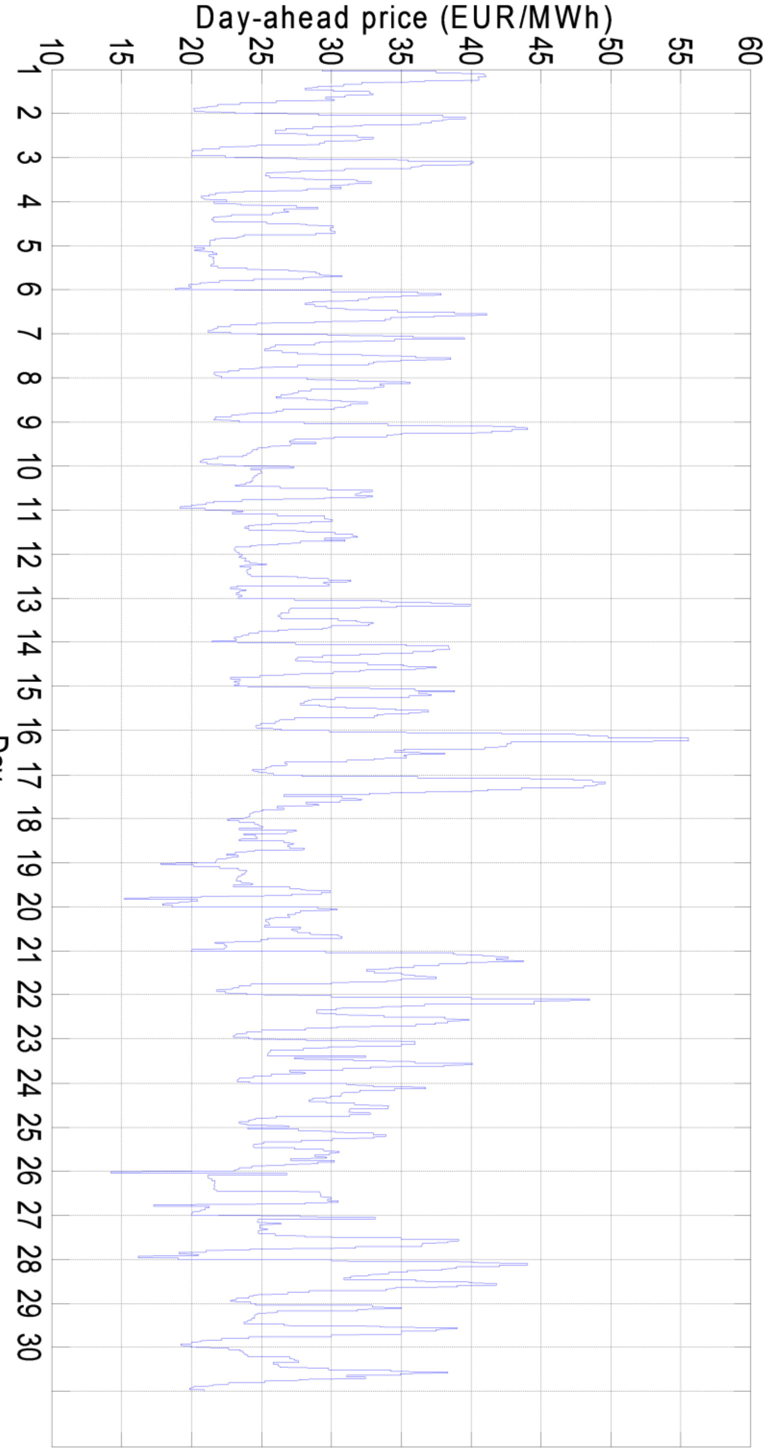

Fig. 3.25 Day-ahead price of 30 days

3.2.3.2 Simulation result

The voltage violation numbers of time during the 30 days of the 3 cases are shown in Fig. 3.26.

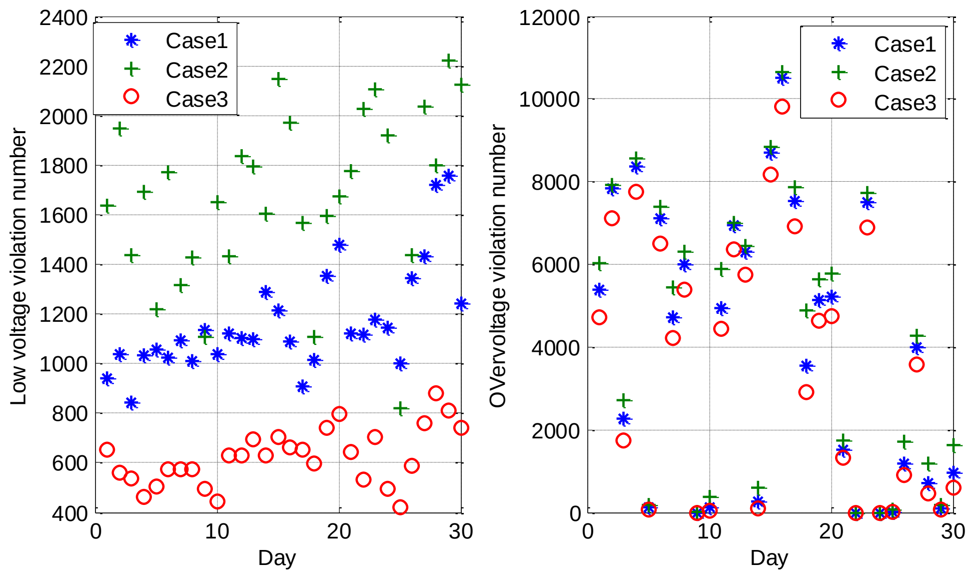

Fig. 3.26 Voltage violation number in 30 days

The simulation result shows that the voltage violation number of case 2 is the most because the purpose of case 2 is only to maximize the profit without considering the voltage condition of the distribution system. In case 3, the objective function is both considering the profit maximization and voltage violation reduction, so the voltage violation number of times is fewer than that in case 2. The voltage violation number in case 3 is also fewer than case 1. It shows that the day-ahead load scheduling method is effective to reduce the voltage violation in the distribution system.

3.3 Conclusion

This chapter proposes a day-ahead load scheduling method. The purpose is to maximize customers' profit and reduce the voltage violation frequency. The problem is formulated as an optimization problem, and GA is utilized to solve the optimization. The proposed method is validated both on 12-customer and 1800-customer distribution system, and 3 cases are considered in the simulation. Comparing the results among the 3 cases, the proposed method can both maximize customers' profit and reduce the voltage violation times through the load scheduling method.

Chapter 4 Real-time Voltage Regulation via CEMS

4.1 Introduction

With the day-ahead scheduling, the SLs are scheduled by each CEMS to maximize the profit and reduce the voltage violation frequency. However, errors are inevitable in the day-ahead estimation of PV and ODL data. Voltage violation may happen because of the estimation data errors. As a result, real-time load rescheduling method is proposed for the real-time operation period.

The real-time load rescheduling method requires a communication network as well as accurate information of real-time load and PV output data. This communication system does not exist in the current power distribution system. However, it is widely accepted that a communication infrastructure is an essential part for the success of an emerging smart grid [72]. If HEMS is widely implemented in the future, DR will become normal in a distribution system. The cost for implementing the proposed method is to build the information network among HEMSs, sub-CEMS, CEMS and DSO, which can likely be realized in the future.

This chapter first introduces the real-time overvoltage prevention via load scheduling. In addition, the reactive power generated by PV inverter is also utilized for the overvoltage regulation. Then, the cooperation between OLTC and load scheduling method is proposed. After that, low voltage prevention via real-time load rescheduling is introduced. At last, the equivalent SVC capacity of the proposed method is carried out to evaluate the voltage regulation of the proposed load scheduling method.

4.2 Real-time overvoltage prevention via load rescheduling in a sub-CEMS

4.2.1 Objective function in real-time operation

The operation of real-time period is to follow the schedule made in day-ahead. When overvoltage or low voltage is anticipated, the objective is to search the minimum capacity of SLs, and then shift the load to mitigate the voltage violation. The objective function of real-time load rescheduling is shown in Eq. (4-1).

$$Min. \quad \sum_{num=1}^{N_c} P_{l^{sl}}^{h,num} \tag{4-1}$$

$$P_{l^{sl}}^{h,num} = \sum_{i=1}^{N_{A_i}} P_{A_i}^{h,num} \cdot SW_{A_i}^{num} \tag{4-2}$$

$$SW_{A_i}^{num} = \begin{cases} 1, & A_i \ is \ on \\ 0, & A_i \ is \ off \end{cases} \tag{4-3}$$

Constraints:

1) Equality constraints

- SL power combination: Eqs. (4-2) and (4-3).
- Nonlinear power flow equations:

$$V^{h,num}(I^{h,num})^* = P_{load}^{h,num} - P_{PV}^{h,num} + j(Q_{load}^{h,num} + Q_{PV}^{h,num}) \tag{4-4}$$

2) Inequality constraints

- Voltage constraint:

$$V_{low} \le V^{h,num} \le V_{high} \tag{4-5}$$

- OLTC tap constraint:

$$O_{tapmin} \le O_{tap} \le O_{tapmax} \tag{4-6}$$

- SLs specification constraint:

$$P_{A_i}^{h,num} = \begin{cases} P_{A_i} \cdot Flag(A_i), & \alpha_{A_i} \le h \le \beta_{A_i} - T_{A_i}^{ot} \\ 0, & others \end{cases} \tag{4-7}$$

$$Flag(A_i) = \begin{cases} 1, & A_i \ is \ unstarted \\ 0, & A_i \ is \ started \end{cases} \tag{4-8}$$

where, h identifies the time slot. num denotes the number of customers in the community, and N_c denotes the total number of customers in the community. $P_{PV}^{h,num}$ and $P_{load}^{h,num}$ are the PV output and demand power [kW], and $P_{l^{sl}}^{h,num}$ and $P_{l^{odl}}^{h,num}$ are the active power of the SLs and ODLs [kW], respectively. N_{A_i} is the number of SLs. $SW_{A_i}^{num}$ is the appliance switch, in which, 1 indicates that A_i is on and 0 indicates that A_i is off. $V^{h,num}$ and $I^{h,num}$ are node voltage and line current, respectively. $Q_{load}^{h,num}$ is the load reactive power, while $\mathrm{Q}_{\mathrm{PV}}^{\mathrm{h,num}}$ is the reactive power of PV. V_{low} is the low limit of voltage and V_{high} is the high limit. O_{tap} is the tap number of OLTC, and O_{tapmin} and O_{tapmax} is the max and min OLTC tap limit respectively, and the regulation step of the OLTC is 0.0125 p.u. per tap.

In the real-time operation, at the beginning of each time slot, each sub-CEMS first estimates the voltage profile of its covering sub-system by tentatively starting the SLs according to the schedule. When overvoltage is anticipated, minimum capacity of un-started SLs will be started to drop the voltage to the permissible range. Because starting different appliance (A_i) at different location customers (*num*) will achieve different voltage regulation effects, the optimization of Eq. (4-1) is to find the minimum combination of $P_{l_{sl}}^{h,num}$ which can suppress the overvoltage. By only rescheduling the minimum capacity of SLs, the day-ahead schedule is followed maximum possible.

4.2.2 Optimization Algorithm

4.2.2.1 VRLCS algorithm

The searching of objective function (4-1) of each sub-CEMS includes power flow calculation, and therefore, it becomes a combinatorial nonlinear problem, which requires heavier computation burden. For a radial power distribution system, two followed features can be utilized for developing a search algorithm.

- First, the most effective way to reduce a certain node voltage is to start a load of its own.
- Second, the voltages at the nodes farther from the distribution substation tend to be more volatile. On the other hand, these nodes have more regulation contribution, i.e., when the SLs at those nodes are started, the voltage can drop by themselves as well as those of the other nodes in the same secondary feeder.

Proof: see section 1.2.5.

To realize real-time control, a fast sequential search method called VRLCS is developed to solve the optimization problem. The VRLCS is developed on the basis of the above-mentioned features of the power distribution system. The objective of the VRLCS is to search a combination of minimum total capacity SLs that can suppress the overvoltage in the sub-CEMS. According to the above-mentioned two features, the search process of the VRLCS is based on voltage ranking. In each search process, the VRLCS searches the customers with the highest voltage and preferentially choose the farthest location customer. Then VRLCS increase the SL capacity by starting the SL of the customers.

The detailed flowchart of the VRLCS search process is shown in Fig. 4.1. When overvoltage is anticipated in a time slot, the VRLCS checks the available SL and generates a set of SL capacity combination. If there are *n* available SLs with different power, there will be 2^n combinations according to the on/off status of the *n* SLs. Then the 2^n combined SL capacities are sorted in the ascending order. For example, if there are four kinds of available SLs with the power of 0.3, 0.4, 0.5 and 1.5 kW, there will be 16 combinations considering the on/off status of the switches. The combined power list of the example is shown in Table 6.

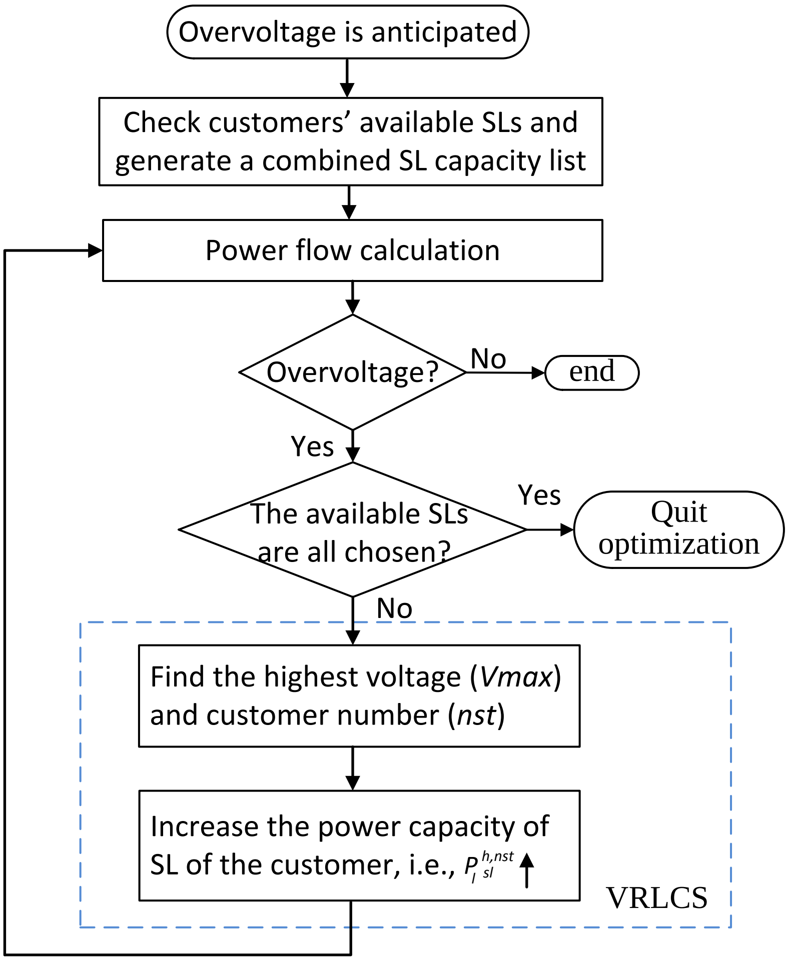

Fig. 4.1 Flowchart of VRLCS process

Table 6 Combined power list

	Power (kW)	Switch (1: on; 0: off)															
SL 1	0.3	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
SL 2	0.4	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
SL 3	0.5	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
SL 4	1.5	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
Combined power (kW)		0	1.5	0.5	2	0	1.9	1	2.4	0.3	1.8	0.8	2.3	0.7	2.2	1.2	2.7
Power ascending list(kW)		0	0.3	0.4	0.5	1	0.8	1	1.2	1.5	1.8	1.9	2	2.2	2.3	2.4	2.7

The next step is power flow calculation. After that is to find the highest voltage customer, and then increase one step SL capacity in the combined power ascending list. The above process is continued unless that the SL capacity is enough for solving overvoltage or in case that overvoltage still cannot be solved when all available SLs are chosen. In the latter case, starting SL is not capable to solve the overvoltage. The VRLCS quits the optimization, SLs will not be started, and OLTC will operate.

4.2.2.2 GA

GA is widely applied in power system nonlinear optimization. However, the search of GA is based on random genetic mutation and chromosome crossover but does not consider specific system features. As a result, the calculation time of GA is relatively long.

For the comparison, GA method is also applied to search the minimum capacity of SLs for solving the optimization problem. The GA replaces the process of VRLCS in Fig. 4.1. At first, the GA creates an initial solution population, the chromosomes of which are all the available SLs of each customer. Then GA starts the evolution of the population. At the beginning of each generation, the GA checks the chromosomes through power flow calculation, and the ones cannot solve overvoltage will be replaced by the available chromosome. The next step is fitness function calculation and chromosomes ranking. The fitness function of GA is Eq. (4-1). After the ranking, the top-2 chromosomes are kept, and other chromosomes do the process of crossover and mutation. After that a new solution population is generated, and the GA goes to next generation. The GA repeats the process of chromosome check, fitness function evaluation, crossover and mutation. Finally, the GA stops the iteration when reaches the expected generation number.

4.2.2.3 Voltage sensitivity algorithm

Voltage sensitivity algorithm is widely used for determining the locations and amounts of reactive power for the grid voltage support from the distributed solar inverters. A voltage sensitivity matrix S (Eq. (4-12)) is derived by solving two nonlinear load flow Eq. (4-9) and (4-10) using Newton–Raphson algorithm. The system Jacobian matrix is updated at each iteration until convergence tolerance is satisfied and the resultant Jacobian matrix is inversed to compute S matrix [43][73]–[75].

$$P_i = |U_i| \sum_{j=1}^{n} |U_j| |Y_{ij}| cos(\theta_{ij} - \delta_i + \delta_j) \tag{4-9}$$

$$Q_i = -|U_i| \sum_{j=1}^{n} |U_j| |Y_{ij}| sin(\theta_{ij} - \delta_i + \delta_j) \tag{4-10}$$

$$\begin{bmatrix} \Delta\theta \\ \Delta U \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{4-11}$$

$$S = J^{-1} = \begin{bmatrix} S_{\theta P} & S_{\theta Q} \\ S_{UP} & S_{UQ} \end{bmatrix} \tag{4-12}$$

In Eq. (4-11), the relation of Δθ and ΔU is decoupled. Then the ΔU can be calculated from the Eq. (4-13).

$$\Delta U = S_{UP} \cdot \Delta P + S_{UQ} \cdot \Delta Q \tag{4-13}$$

The reactive power is not considered in this section. The objective of Eq. (4-1) is to find the minimum capacity of active power to regulate the overvoltage. Setting the ΔQ = 0 in the Eq. (4-13), and then the ΔP which is needed to regulate the voltage can be calculated from Eq. (4-14).

$$\Delta P = S_{UP}^{-1} \cdot \Delta U \tag{4-14}$$

Similar to VRLCS and GA method, Eq. (4-14) can be used to search the minimum capacity of SLs to solve the overvoltage. The sensitivity method replaces the process of VRLCS in Fig. 4.1. The detailed process of voltage sensitivity method is shown in Fig. 4.2.

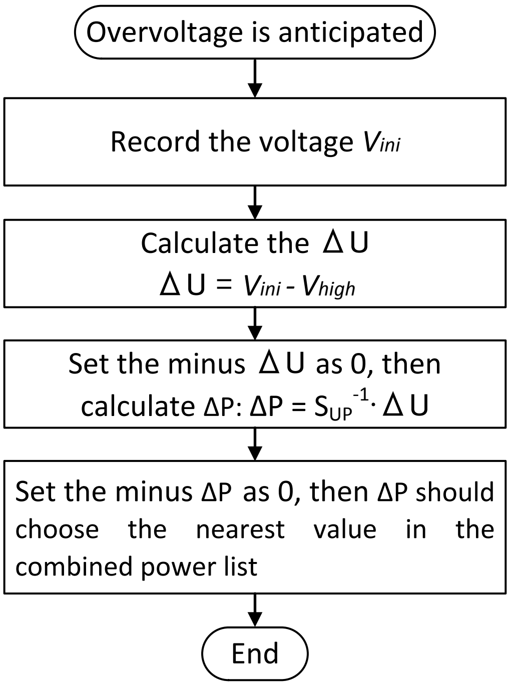

Fig. 4.2 Voltage sensitivity method process

When overvoltage is anticipated, the first step is to record the voltage, and the second step is to calculate the ΔU, which is the amount to regulate the voltage to the permissible range. The minus ΔU means that the voltage is under the high limit, and load rescheduling is not needed at these nodes. After that, the Δ*P* can be calculated by Eq. (4-14). At last, the specific SL can be decided by searching the Δ*P* and combined power list.

4.2.3 Simulation in a sub-CEMS on 2nd June, 2007

4.2.3.1 Simulation condition

The real-time load rescheduling method is first validated on a 12-customer system, and the system model is the same as shown in Fig. 3.5 in section 3.1.3. A rooftop PV system is considered in all of the customers. In this work, the assumed duration of the time slot is 5 min, i.e., a day has 288 time slots or $h \in [1, 288]$. In other words, the PV and ODL power is assumed unchanged within 5 min.

The simulation is carried out on 2nd, June 2007. The data of the PV and ODL are referred from the demonstration project conducted by NEDO in Ota City, Japan. In this database, the data is recorded in every second. The data is transferred into 288 time slots by taking the average. The load and PV data shapes are similar with the data in Fig. 3.6 and Fig. 3.7 in section 3.1.3.1. The SLs data is almost same with the data in Table 1, but the EV is not considered here. The starting time of SLs are referring to the day-ahead schedule of case 3 in section 3.1.3.2. To combine the simulation of day-ahead and real-time operation, the starting time of SLs in day-ahead period is transferred to real-time operation by change the time slots properly. For example, the time slot number 13 indicates 9:00 in day-ahead simulation; however, the time slot number of 9:00 in real-time simulation is 37. The time slot transformation equation is shown in (4-15).

$$h_{real\_time} = 3 * \left(h_{day\_ahead} - 1\right) + 1 \tag{4-15}$$

Overvoltage violation does not happen in the case 3 in section 3.1.3.2. To test the real-time overvoltage solution, the sending voltage at the pole transformer is set as 1.0375 p.u. to amplify the overvoltage condition. The overvoltage and low voltage point is set as 107 V and 95 V, respectively. The following three cases are considered in the simulation.

Case 1: no real-time load rescheduling.

Case 2: real-time load rescheduling using voltage sensitivity method.

Case 3: real-time load rescheduling using GA method.

Case 4: real-time load rescheduling using VRLCS method.

In case 1, real-time load rescheduling is not applied, and all SLs are started following the day-ahead schedule. For case 2, case 3 and case 4, SLs are optimally searched by following the objective function (4-1) for the purpose of following day-ahead schedule and regulating the overvoltage.

4.2.3.2 Simulation result

An intraday simulation is carried out on 2nd June 2007 for the four cases. In case 1, the SLs are started according to the day-ahead schedule of case 3 in section 3.1.3.2, and then the voltage of the 288 time slots is recorded. For case 2, case 3 and case 4, at the beginning of each time slot, the sub-CEMS first estimates the voltage profile of its covering sub-system by tentatively starting the SLs according to the day-ahead schedule. When overvoltage is anticipated, minimum capacity of un-started SLs will be searched and started to drop the voltage to the permissible range. For these three cases, the decisions of minimum capacity of SLs are carried out by voltage sensitivity method, GA method and VRLCS method, respectively. The overvoltage violation numbers and SLs amount of real-time rescheduling of the four cases are shown in Table 7.

Table 7 Simulation results of the four cases

	Overvoltage violation number	**SLs capacity used in real-time rescheduling (kWh)**	**Longest optimization time in one time slot (s)**
Case 1	59		
Case 2	39	10.41	0.094
Case 3	7	5.18	4.92
Case 4	4	4.25	0.032

Because the sending voltage at the pole transformer is set as 1.0375 p.u. to amplify the overvoltage condition, overvoltage happens 59 times if the SLs are started just following the day-ahead schedule. With the real-time load rescheduling carried by the optimization method in case 2, case 3 and case 4. The violation numbers of overvoltage are decreased. However, the voltage sensitivity method is not so effective to prevent the overvoltage. In case 3 and case 4, the GA method and the VRLCS method can decrease the overvoltage to 7 times and 4 times. The VRLCS method achieves the lowest number of overvoltage violation. In addition, the SLs capacity used in real-time rescheduling of case 4 is also the least. For this result, it shows that the VRLCS method achieved the best result of the objective function Eq. (4-1).

The simulation is carried out using MATLAB software in a typical personal computer with a CPU of Intel(R) Core(TM) i7-4770 @ 3.40GHz and 8 GB memory. The power flow calculation time is approximately 0.0035 s for a 12-customer CEMS using the backward/forward algorithm. The longest calculation time of the VRLCS method is 0.025 s, while the longest calculation time of the GA method is 4.92 s. The searching time of GA method is much longer than the VRLCS method because GA reaches the result by many times of iteration. Time-consuming power flow calculation is carried out in each time of iteration. The 12-customer voltage conditions of the four cases are shown in Fig. 4.3, Fig. 4.4, Fig. 4.5 and Fig. 4.6. The final SLs working schedule of the four cases are shown in Fig. 4.7.

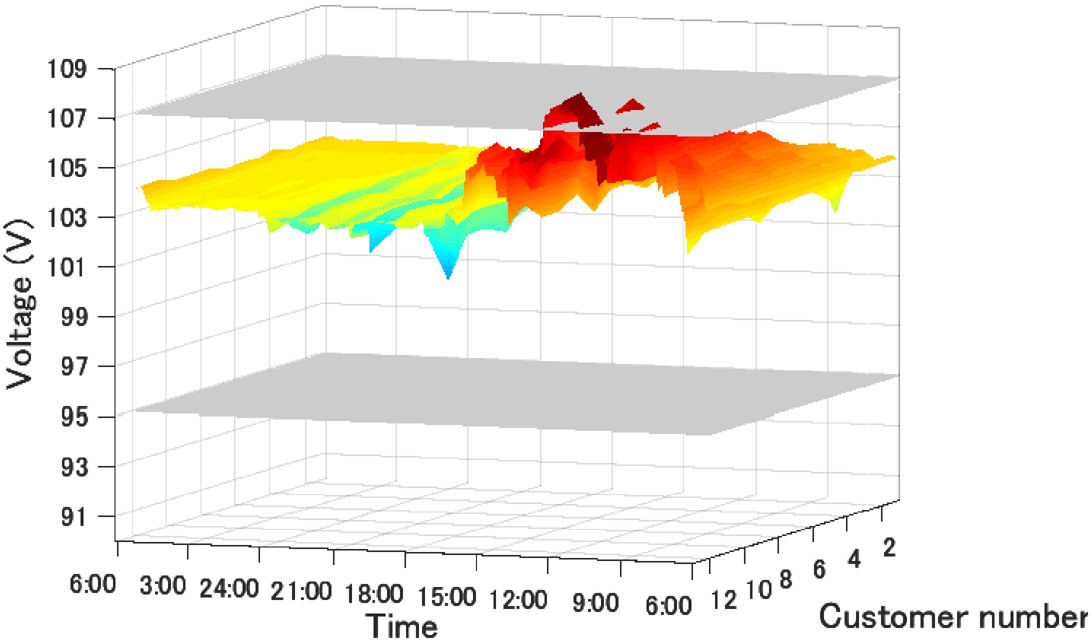

Fig. 4.3 12-customer voltage condition of case 1

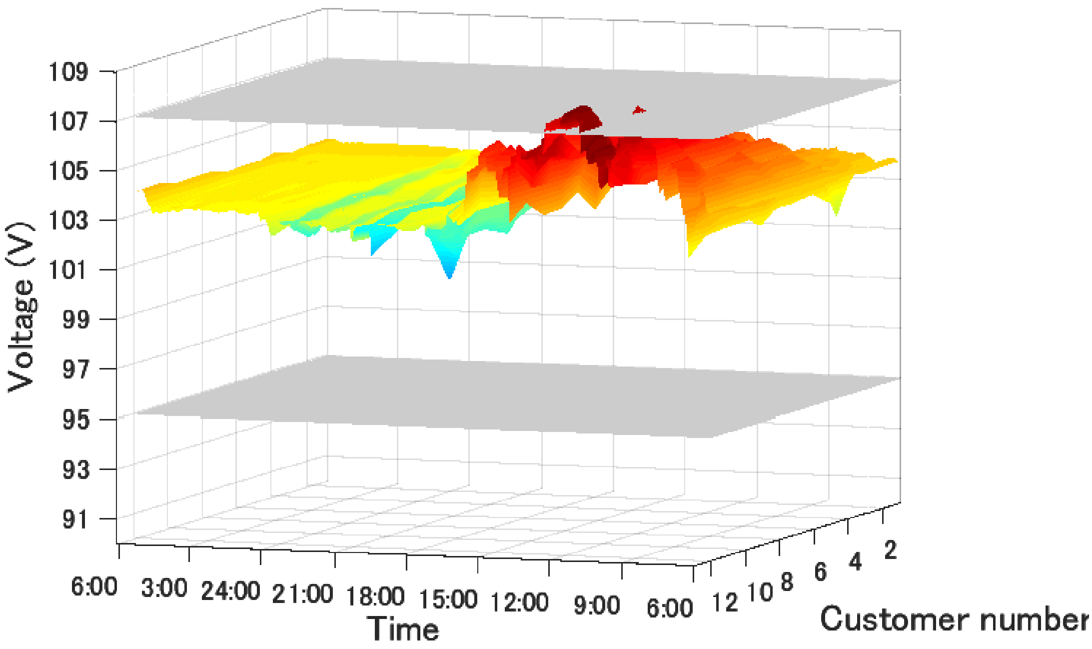

Fig. 4.4 12-customer voltage condition of case 2

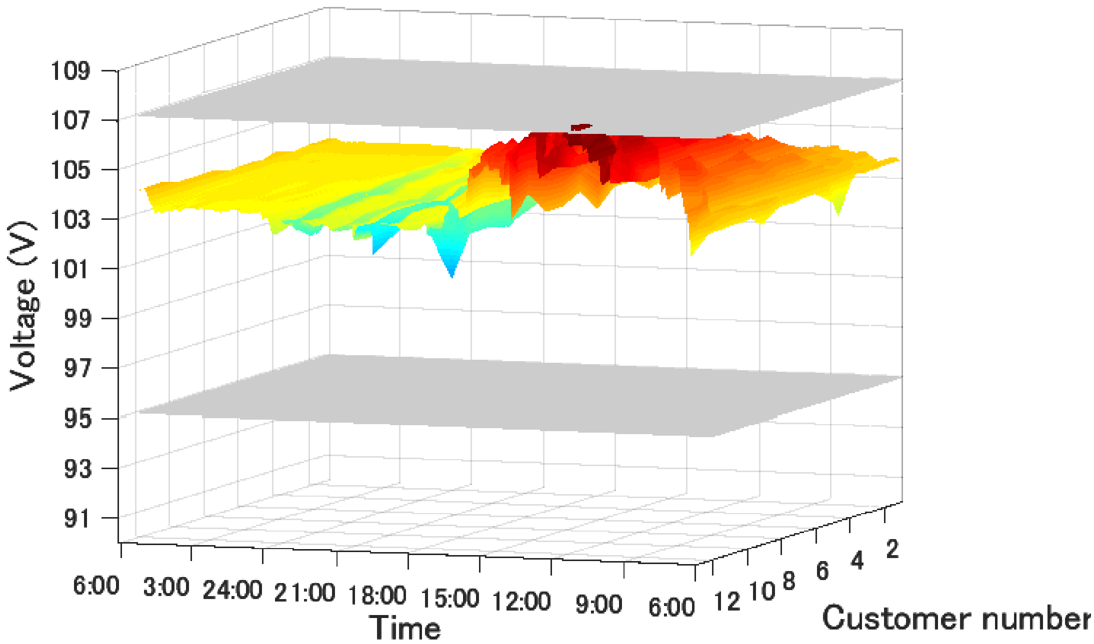

Fig. 4.5 12-customer voltage condition of case 3

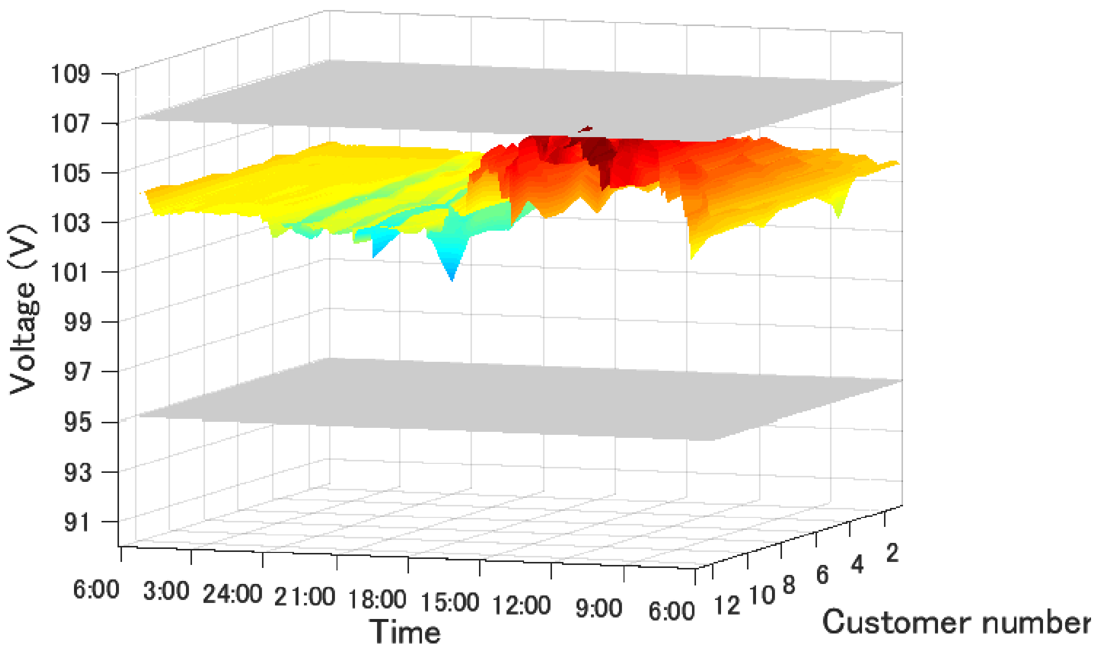

Fig. 4.6 12-customer voltage condition of case 4

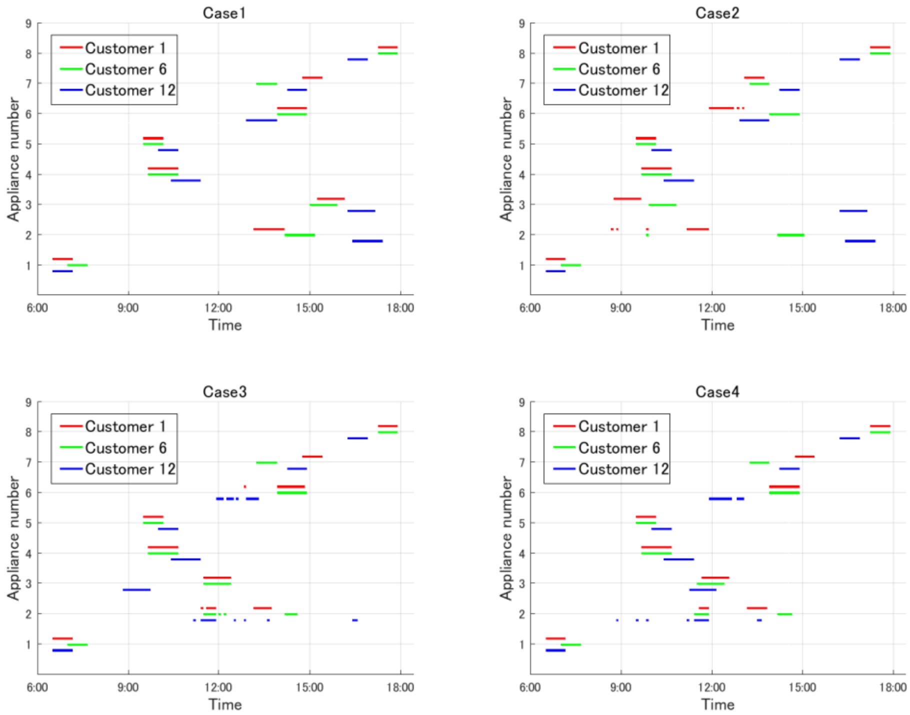

Fig. 4.7 The final SLs working schedule of the four cases

4.3 Real-time overvoltage prevention via load rescheduling in multi-sub-CEMSs

4.3.1 Interaction between CEMS and sub-CEMSs

As mentioned in section 2.3, a large power distribution system can be divided into central CEMS and multi-sub-CEMS structure. The sub-CEMS is the integration of customers under the same pole transformer, and the central CEMS is the main controller of the system with the function of coordinating all sub-CEMSs. With knowing the voltage at the pole transformer, each sub-CEMS finishes the above-mentioned real-time load rescheduling optimization separately and concurrently. As described, the announced pole transformer voltage, denoted by V_{ref}, is calculated by the central CEMS using the real-time aggregated net load data of each sub-CEMS. Each sub-CEMS is an independent entity in the SL scheduling; however, starting the SLs by the sub-CEMSs would decrease the primary node voltage. In other words, starting the SLs in one sub-CEMS would help other sub-CEMSs decrease the voltage profile. As a result, initial reference voltage V_{ref} for each CEMS is larger than the optimal one.

To determine V_{ref} for each sub-CEMS, interactions between the central CEMS and sub-CEMSs are needed, the process of which is shown in Fig. 4.8.

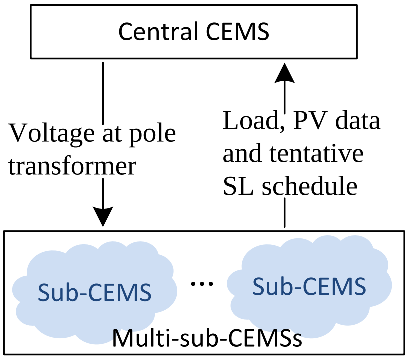

Fig. 4.8 Interaction of central CEMS and multi-sub-CEMS

The proposed scheme assumes that each sub-CEMS updates and sends the aggregated net load data to the central CEMS after first deciding the SL schedule. Then, the central CEMS calculates the primary node voltage again (the updated voltage is denoted by $V_{profile}$). The general process of finding the optimal reference voltage is as follows: decrease V_{ref}, and then each sub-CEMS then reschedules the SL capacity to drop the overvoltage. The total needed SL capacity will be less; thereafter, $V_{profile}$ would increase. According to this process, the optimal reference voltage is a value between V_{ref} and $V_{profile}$; thus, it can be found by iteration, as expressed in Eqs. (4-16) and (4-17).

$$V_{profile}(0) = V_{ref}(0) \tag{4-16}$$

$$V_{ref}(k) = V_{profile}(k-1) + \lambda * \left[V_{ref}(k-1) - V_{profile}(k-1)\right]; k \geq 1 \tag{4-17}$$

where λ is an experimental value between zero and one. A λ value near one will ensure that each $V_{ref}(k)$ is appropriate for the sub-CEMS to decide sufficient SL capacity, but it prolongs the calculation time to reach convergence. On the other hand, a too small λ may not allow the SL capacity decided by the sub-CEMS to suppress the overvoltage. In short, using optimal reference voltage $V_{ref}(k)$, each sub-CEMS decides the optimal capacity of the SL power to deal with the overvoltage and to finally achieve the Nash equilibrium condition.

4.3.2 Simulation in multi-sub-CEMSs on 2nd June, 2007

The real-time load rescheduling method of multi-sub-CEMSs is first carried out on 2nd June, 2007. The starting time of SLs are referring to the day-ahead schedule of case 3 in section 3.2.2. In this case the sending voltage of OLTC is 1.0375 p.u, which is same as that in section 3.2.3. The overvoltage and low voltage point is set as 107 V and 95 V, respectively. VRLCS is used for searching the optimization of Eq. (4-1). The duration of the time slot is 5 min, i.e., a day has 288 time slots or $h \in [1, 288]$. The starting time of SLs in day-ahead period is transfer to real-time operation by change the time slots properly according to Eq. (4-15).

The simulation model is same as the model in section 3.2.2. A rooftop PV system and is considered in all of the customers. The data of the PV and ODL are referred from the demonstration project conducted by NEDO in Ota City, Japan. The data is transferred into 288 time slots by taking the average. The load and PV data shapes are similar with the data in Fig. 3.24 in section 3.2.2. The SLs data is almost same with the data in Table 1, but the EV is not considered here.

4.3.2.1 Result of real-time load rescheduling

The starting time of SLs are referring to the day-ahead schedule of case 3 in section 3.2.3. The charging of EVs is not considered here. In the real-time operation, if real-time load rescheduling is not applied for preventing the overvoltage. The overvoltage violation number of time is 15254, and the profit is 1810.74 EUR. After applied the real-time load rescheduling for preventing the overvoltage, the overvoltage violation number of time is reduced to 5762, and the profit is 1,786.94 in the case that the interaction number between the central CEMS and sub-CEMSs is 1.

4.3.2.2 Result of the interaction between the Central CEMS and sub-CEMSs

The λ value in Eq. (4-17) in Section 4.3.1 of the interaction between the central CEMS and sub-CEMSs is an experimental value. λ = 0.7 is a safe value, and the iteration can quickly achieve convergence. The result under different iteration numbers are listed in Table 8. The SL usage indicates the total SL capacity utilized in the overvoltage regulation. Surplus power injection means the customer electrical power sold to the utility company. Considering the purpose of the optimization problem formulation, the lesser the SL capacity utilized in the overvoltage regulation is, the more surplus power can be sold to the power company. The total profit listed in Table 8 is the profit after overvoltage regulation.

The iteration results show that the more the iteration times are, the lesser is the SL capacity combination that needs to be shifted. In other words, more profit can be achieved according to the day-ahead schedule, i.e., the result is better. However, more iteration times incur longer calculation time, which is a disadvantage in real-time control. Fig. 4.9 shows that after three iterations, the SL usage reduction is relative little and the total profit increment is little. Considering the calculation time, three iteration times is chosen in the following simulation.

Table 8 Result of the iteration between the Central CEMS and sub-CEMSs

Iterations	SL usage (kWh)	Surplus power injection (kWh)	Total profit (EUR)
1	722.16	19,952.16	1,786.94
2	700.41	19,954.52	1,787.26
3	682.93	19,956.49	1,787.45
4	675.50	19,959.53	1,787.60
5	666.23	19,961.10	1,787.73
6	664.13	19,961.57	1,787.76

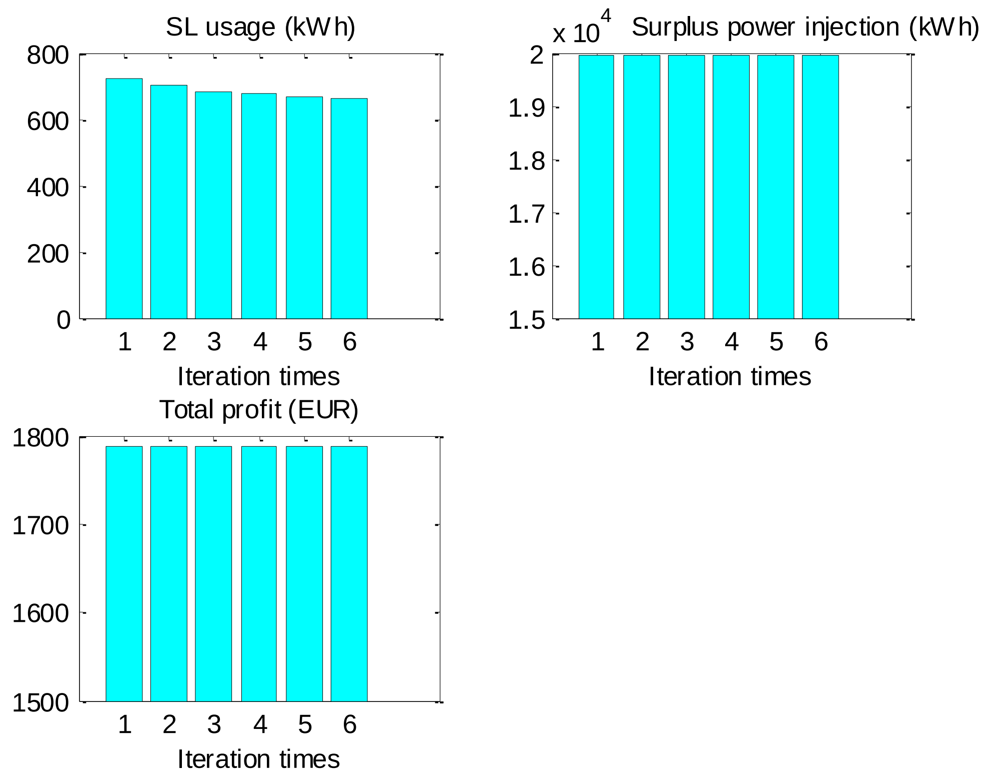

Fig. 4.9 Result of the iteration between the Central CEMS and sub-CEMSs

4.3.2.3 Calculation speed

The simulation is carried out using MATLAB software in a typical personal computer with a CPU of Intel(R) Core(TM) i7-4770 @ 3.40GHz and 8 GB memory. The power flow calculation time is approximately 0.0035 s for a 12-customer CEMS using the backward/forward algorithm. The longest calculation time of the VRLCS is 0.075 s. As mentioned in section 4.3.2.2, three times of interaction between central CEMS and sub-CEMSs can help achieve a better solution, so the total optimization time is approximately 2.25 s. Besides, the communication time between central CEMS and sub-CEMSs should be added. However, because the communication network does not exist at present, it is difficult to evaluate the communication time in the simulation. In section 4.3.1, it costs about 0.068 s for the central CEMS to calculate the whole system power flow and decide the operation of OLTC, i.e., the operation time of the flow chart in Fig. 4.14 except CEMSs searching time. In short, the total calculation time is less than 3 s not including communication time, which is applicable in a real-time control with a 5-min interval.

4.4 Real-time voltage control via reactive power generated by PV

The above-mentioned methods utilize load rescheduling to deal with the overvoltage violation problem, in other words, only active power regulation is considered. However, reactive power regulation is the most common way for voltage control. In nowadays, some of the PV inverter has the reactive power generation function. The PV inverter can absorb reactive power to regulate the overvoltage while not reducing the active power output. The constraints of reactive power are as shown in Eq. (4-18) and (4-19).

PV reactive power constraint:

$$-\sqrt{S_{max}^2 - P_{PV}^2} \leq Q_{PV} \leq \sqrt{S_{max}^2 + P_{PV}^2} \tag{4-18}$$

Power factor (PF) constraint:

$$PF = COS(tan^{-1}(\frac{Q_{PV}}{P_{PV}})) \tag{4-19}$$

In the distribution system, the PF should be in a proper range. If the absolute value of PF is too small, it will increase power loss without delivering much active power. In the simulation, the absolute value of PF is limit to 0.85.

Continuing the simulation in section 4.3.2, reactive power regulation is also applied in the overvoltage regulation. Because the reactive power generation does not affect the customers' profit, the reactive power regulation should be carried out before the process of load rescheduling. At the beginning of each time slot, each sub-CEMS first estimates the voltage profile of its covering sub-system by tentatively starting the SLs according to the schedule. If overvoltage is anticipated, the max capable amount of reactive power is generated (absorbing) to decrease the voltage. If reactive power regulation is not able to solve all the overvoltage, then the load rescheduling method will be carried.

The simulation is carried out with the same condition as section 4.3.2, and the result shows that the overvoltage violation number is reduced to 245 times under the assistant of reactive power generation.

4.5 OLTC Operation Strategy of overvoltage

The OLTC operation will become more frequent due to the presence of the PVs, especially in cloudy days when the PV fluctuation is high. Frequent OLTC operation will result in an increase in the maintenance cost. However, if the household load can be utilized in the voltage regulation, a large amount of maintenance cost and new devices construction will be saved. In the proposed central CEMS and sub-CEMS structure, the customer household loads can be utilized for voltage regulation to relieve the operating stress in these voltage regulation devices.

Line-drop-compensation control is a traditional OLTC control strategy; however, the purpose of this part is to evaluate the effectiveness of a load scheduling method for overvoltage prevention. A coordinated control of the OLTC and central CEMS is proposed. The basic OLTC operating strategy is described as follows: in each time slot, the sub-CEMS first try to solve the overvoltage. When the SL capacity is insufficient to solve the overvoltage, the sub-CEMS will not operate the SLs, and the OLTC decreases its tap value.

In fact, the optimization of Eq. (4-1) is coupled with the operation of the OLTC. A lower OLTC tap can reduce the voltage output at the substation and decrease the overvoltage level or even prevent overvoltage. However, the objective of this study is to reduce the number of tap operations of the OLTC and then maximize the profit of each sub-CEMS. An improved OLTC operation strategy is shown in Fig. 4.10. The sub-CEMS operation in the current time slot will also consider the future time slot. For example, in the current time, the required SL capacity for overvoltage regulation is $CSLt_0$. Then, if the remaining SLs in next time slot $CSLt_1$ is much less than those in $CSLt_0$, the OLTC will likely need to operate in the next time slot. In this situation, the OLTC can better operate at the current time to save the SL usage. In Fig. 4.14, parameter $c1$ is used to indicate how much lesser is $CSLt_1$ than $CSLt_0$. For example, on a sunny day morning, the PV output increases. The value of c should be larger than one, i.e., more SLs are needed in the next time slot. However, it is difficult to specify how much extra SLs capacity is needed corresponding to PV increment. For simplicity, the simulation selects 1.2 for a sunny day morning, similarly, 0.8 for a sunny day afternoon, 0.5 for a cloudy day, and 1 for a rainy day.

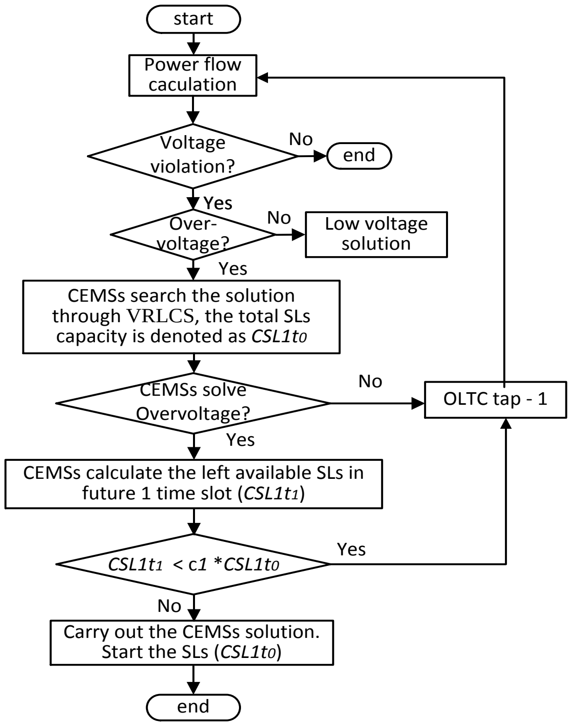

Fig. 4.10 Improved OLTC operation strategy of overvoltage

The OLTC operation to solve the overvoltage on 2nd June is shown in Fig. 4.11. The red full line shows the OLTC operation with the proposed method, and the operation time is 1. In the simulation, once overvoltage is anticipated, each sub-CEMS first generated reactive power from the PVs to drop the voltage, if the overvoltage cannot be solved, then the sub-CEMSs search the minimum capacity of SLs to suppress the overvoltage. Owing to the assistant of sub-CEMSs, the OLTC can reduce the operation times. In contrast, the broken blue line is the OLTC operation without the proposed method, and the total operation time 2. Without the real-time operation, there are more overvoltage violations, and OLTC needs to operate one more time to suppress the overvoltage.

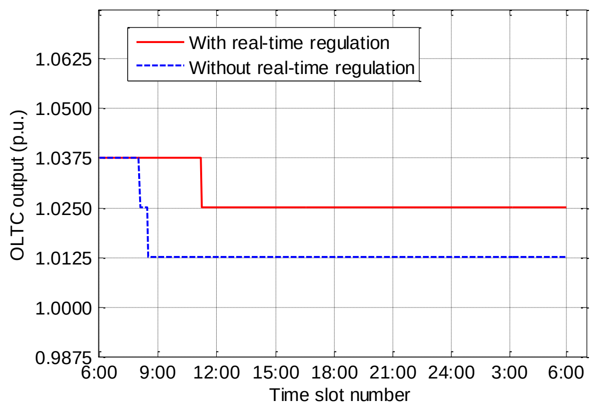

Fig. 4.11 OLTC operation schedule of 2nd June, 2007

4.6 Comparison of proposed method and active power curtailment method

Active power curtailment (APC) method is the normal solution when customers suffer overvoltage. The comparison of the proposed method with APC is shown in Table 9. For the fairness of the comparison, the OLTC operation schedule is set as same as the operation schedule of the proposed method in Fig. 4.11 (red line), and the voltage point for PV active power curtailment is set as 107 V. Because there are some overvoltage violations under the schedule of OLTC, 378.61 kWh of PV power should be curtailed according to the droop method of APC [49]. In contrast, the proposed method mitigates the overvoltage by real-time reactive power generating and SLs rescheduling, so PV curtailment is unnecessary. As a result, the profit of proposed method is higher than APC method (see the profit histogram of Fig. 4.12).

Table 9 Comparison with APC and proposed method

	APC method	Proposed method
Total PV Active power curtailment (kWh)	378.61	0
Total PV power (kWh)	37763.80	38142.42
Total load power (kWh)	32172.76	
Surplus power injection (kWh)	19778.65	20170.00
Total profit (EUR)	1869.18	1913.26

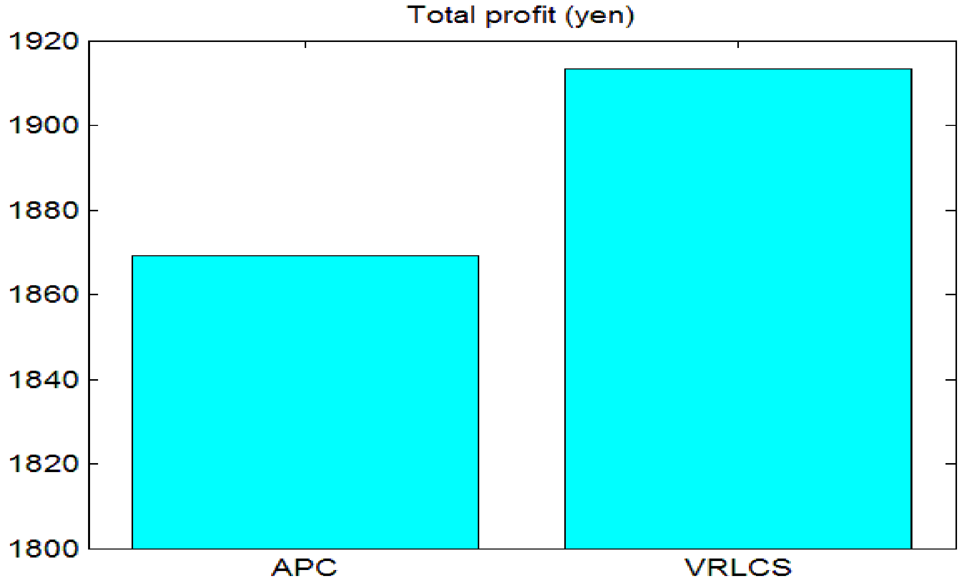

Fig. 4.12 Comparison with APC and proposed method

4.7 Real-time low voltage prevention via load rescheduling

Low voltage problem may happen when large amount of EVs are charging at the same time. Similar to the load rescheduling method in overvoltage solution, in case a low voltage is anticipated, stopping and delaying a minimum capacity of loads can prevent the low voltage. As a result, the VRLCS algorithm can also be applied for searching the minimum SLs capacity which can prevent the low voltage.

The search process of the VRLCS for low voltage prevention is based on voltage ranking. In each search process, the VRLCS searches the customers with the lowest voltage and preferentially choose the farthest location customer. Then VRLCS decrease the SL capacity by stopping the SL of the customers.

The detailed flowchart of the VRLCS search process for low voltage prevention is shown in Fig. 4.13. When low voltage is anticipated in a time slot, the VRLCS first checks the available SLs, which can be stopped at current time slot and delayed the operation time. And then a set of SL capacity combination list will be generated. For example, if there are n available SLs with different power, there will be 2^n combinations according to the on/off status of the n SLs. Then the 2^n combined SL capacities are sorted in the ascending order. The next step is power flow calculation. After that is to find the lowest voltage customer, and then decrease one step SL capacity in the combined SL capacity list. The above process is continued unless that the SL capacity is enough for solving low voltage or in case that low voltage still cannot be solved when all available SLs are chosen. In the latter case, stopping SL is not capable to solve the low voltage. The VRLCS quits the optimization, SLs will not be stopped, and OLTC will operate.

Continuing the simulation in section 4.3.2, EVs are also considered in the simulation. In this section, the SLs specification is same as Table 1, and the EVs starting time are referring to the day-ahead schedule of case 3 in section 3.2.2. The low voltage violation times are 1500 if real-time load rescheduling method is not applied. After applied the load rescheduling for low voltage solution, the low voltage violation can be avoided.

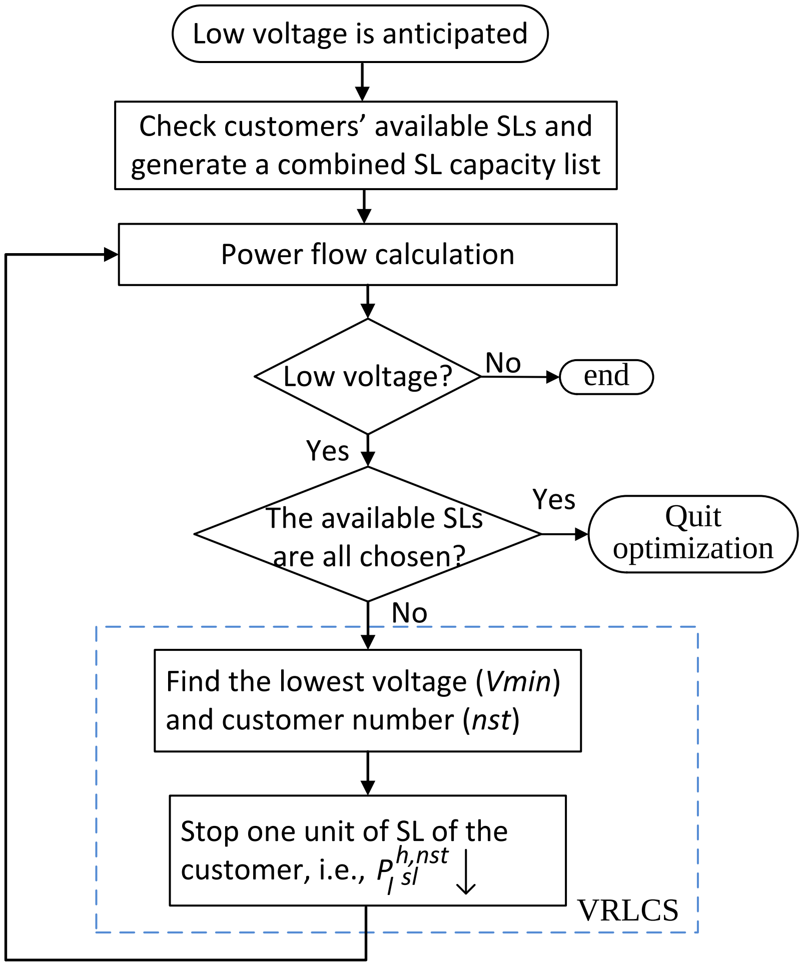

Fig. 4.13 flowchart of the VRLCS search process for low voltage prevention

4.8 OLTC Operation Strategy of low voltage solution

A coordinated control of the OLTC is proposed. The basic OLTC operating strategy is described as follows: in each time slot, the sub-CEMS first try to solve the low voltage. When the available SL capacity is insufficient to solve the low voltage, the sub-CEMS will not operate the SLs, and the OLTC operates the tap and increase its sending voltage. An improved OLTC operation strategy is shown in Fig. 4.14. The sub-CEMS operation in the current time slot will also consider the future time slot. For example, in the current time, the required SL capacity for low voltage regulation is $CSL2t_0$, and the total available SLs capacity is *CSLT*. If the SLs capacity needed to be stopped and delayed is too much, there will be another peak load in the future time slot, and there will be more low voltage violation. In this situation, the OLTC can better operate at the current time to save the SL usage. In Fig. 4.14, parameter *c2* is used to indicate how much percent is $CSLt_0$ of *CSLT*. However, the parameter *c2* is depends on the distribution system model. For simplicity, this simulation set $c2 = 0.1$.

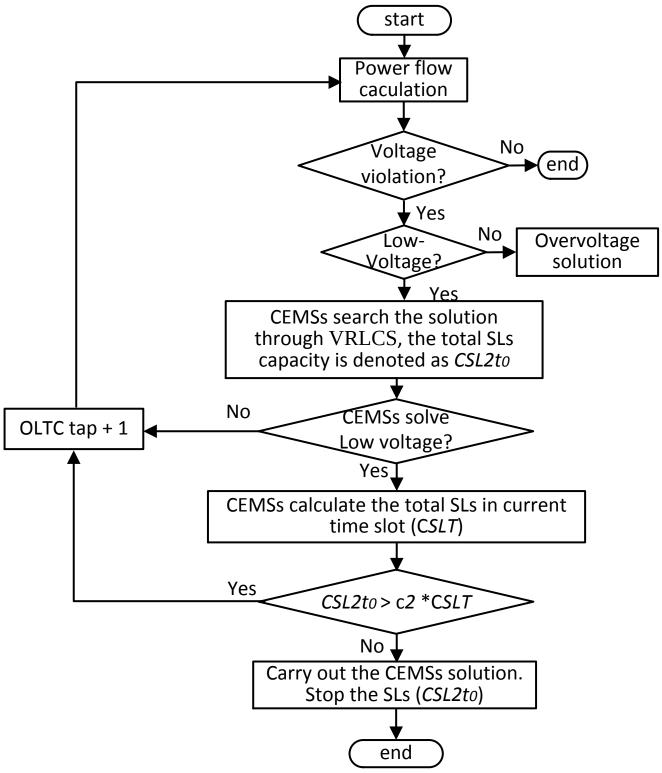

Fig. 4.14 Improved OLTC operation strategy of low voltage

The OLTC operation to solving the overvoltage and low voltage on 2nd June is shown in Fig. 4.15.

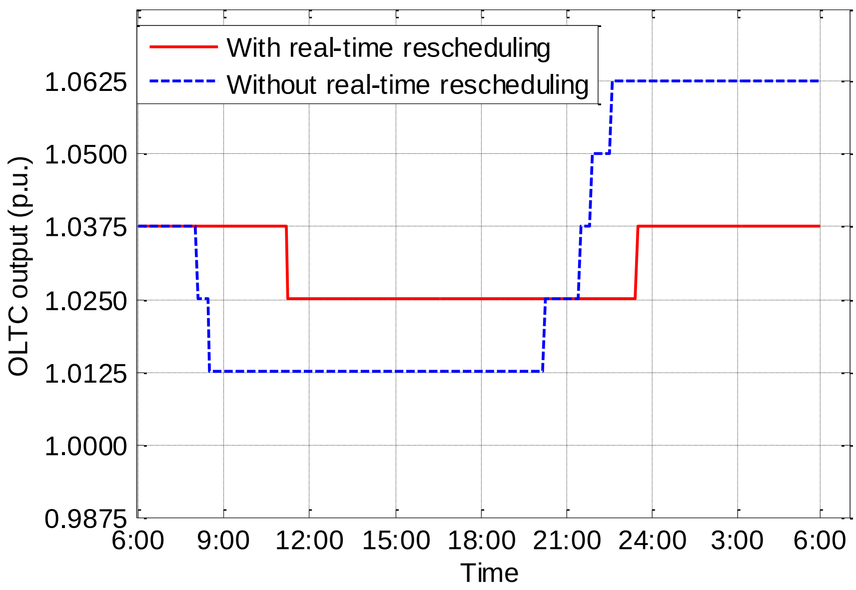

Fig. 4.15 30 days OLTC operation schedule

The red full line shows the OLTC operation with the proposed method, and the total operation times are 2. In the simulation, once voltage violation is anticipated, each sub-CEMS searches the minimum capacity of SLs to suppress the violation. Owing to the assistant of sub-CEMSs, the OLTC can reduce the operation times. In contrast, the broken blue line is the OLTC operation without the proposed method, and the total operation times are 6. The SLs are starting following the day-ahead schedule; in other words, real-time load rescheduling is not utilized for voltage regulation. Under this case, the OLTC needs operate 4 times more for the voltage control. This result shows that with the sub-CEMSs assistant, the operating stress of the OLTC can be relieved.

4.9 Simulation in multi-sub-CEMSs in 30 days

The simulation is carried out on a 1800-customer distribution system in a month period of June 2007. All of the customers are installed with a PV and EV. The data of the PV and ODL are referred from the demonstration project conducted by the NEDO in Ota City, Japan. In this database, the data is recorded in every second. The data is transferred into 96 time slots in day-ahead simulation and 288 time slots in real-time simulation by taking the average. The day-ahead PV and ODL data is the real data within some errors, while in the real-time operation, the PV and ODL data is the real data which are similar with the data in Fig. 3.24 in section 3.2.3. The SLs starting time are referring to the day-ahead simulation result of section 3.2.3.

Three cases are considered in the simulation:

- Case 1: no optimization. SLs are randomly started.
- Case 2: profit maximization without voltage regulation
- Case 3: profit maximization with voltage regulation.

Among the three cases, case 1 indicates that load scheduling method is not applied. Customers' SLs are working in an arbitrary time during the allowed working time period. Case 2 indicates that the load scheduling method is just for the purpose of profit maximization but not considering the voltage violations. Case 3 the proposed method, the purpose of which is to maximize the profit and try to reduce the voltage violation frequency.

The total profit of the whole 1800 customers and OLTC operation times of the 30 days are shown in Table 10. From the OLTC operation number, we can see that with the assistance of real-time voltage regulation carried by the CEMS, the operation number is greatly reduced in case 3. However, it will reduce the profit of the customers.

Table 10 simulation result of three cases

	Total profit (EUR)	OLTC operation number
Case 1	-6,977.5	248
Case 2	-3,910.6	256
Case 3	-6,281.3	38

The OLTC operation of the 30 days of the three cases are shown in Fig. 4.16. Comparing the three cases, the OLTC operation number is greatly reduced in case 3.

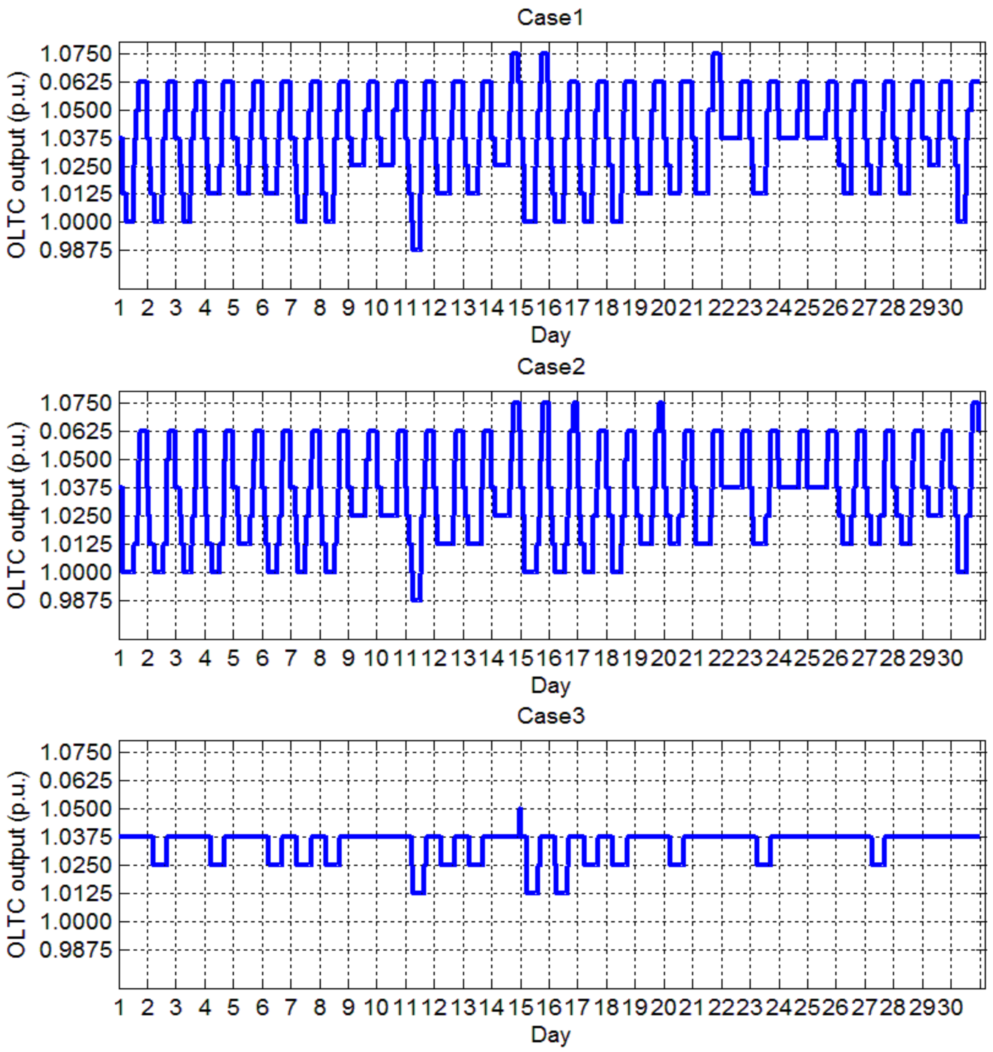

Fig. 4.16 OLTC operation of three cases in 30 days

Among the three cases, the optimization of case 2 is only focused on customers' profit maximization. SLs are scheduled to work in the low price period to save the electricity expense, however, it will cause peak load and make the low voltage violation problem more serious. Furthermore, SLs are scheduled not to work during the time period when PV output is high. The purpose is to generate more surplus power to achieve more profit from FIT. However, this action will make the overvoltage problem more serious. From Fig. 4.16, we can see the OLTC operation frequency is the most among the three cases. In case 3, with assistance of load scheduling carried by CEMS, the voltage regulation pressure of the DSO can be relieved.

4.10 Evaluation of the CEMS in voltage regulation

Installing the SVC in the distribution system is a conventional voltage control method from the perspective of DSO [41], [76], [77]. This research evaluates the voltage control function of the proposed method by calculating an equivalent SVC capacity. Because the voltage at the farther location from substation tends to be more volatile in the distribution system, the SVC is assumed to be installed at the end of the primary nodes (see Fig. 4.17).

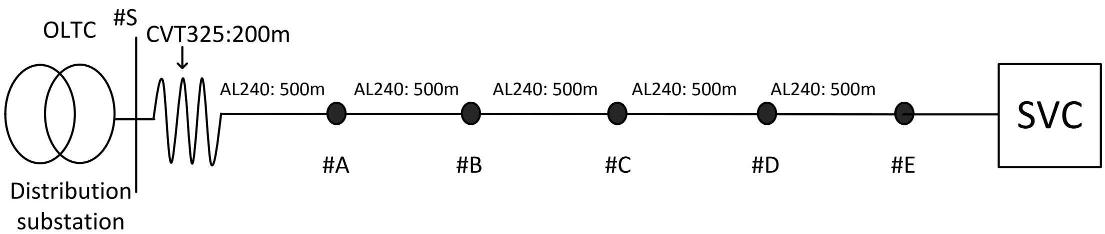

Fig. 4.17 Distribution system model primary nodes with SVC

The evaluation process is proposed as follows:

1) First set a fixed value of SVC capacity (C_{SVC}). For example, $C_{SVC} = 500$ kVar. the starting time of SLs are set with a random value, i.e., $T_{Ai}^{radmstart} \epsilon [\alpha_{A_i}, \beta_{Ai} - T_{Ai}^{ot}]$
2) If Voltage violation happens, SVC generates reactive to regulate the voltage. The method is to increase or decrease SVC output by step of 20 kVar. When the SVC output excess the absolute fixed value ($|C_{SVC}|$), i.e., SVC cannot solve the violation, then OLTC operate
3) Record the OLTC operation number of the 30 days. When the operation number is similar as the load scheduling method, then record this capacity as the equivalent capacity.

In the simulation, the SVC capacity is set as 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000 kVar. The OLTC operation of the above eight SVC capacity values are shown in Fig. 4.18Fig. 4.18 . The OLTC operation number of the above eight SVC capacity values are shown in Table 11.

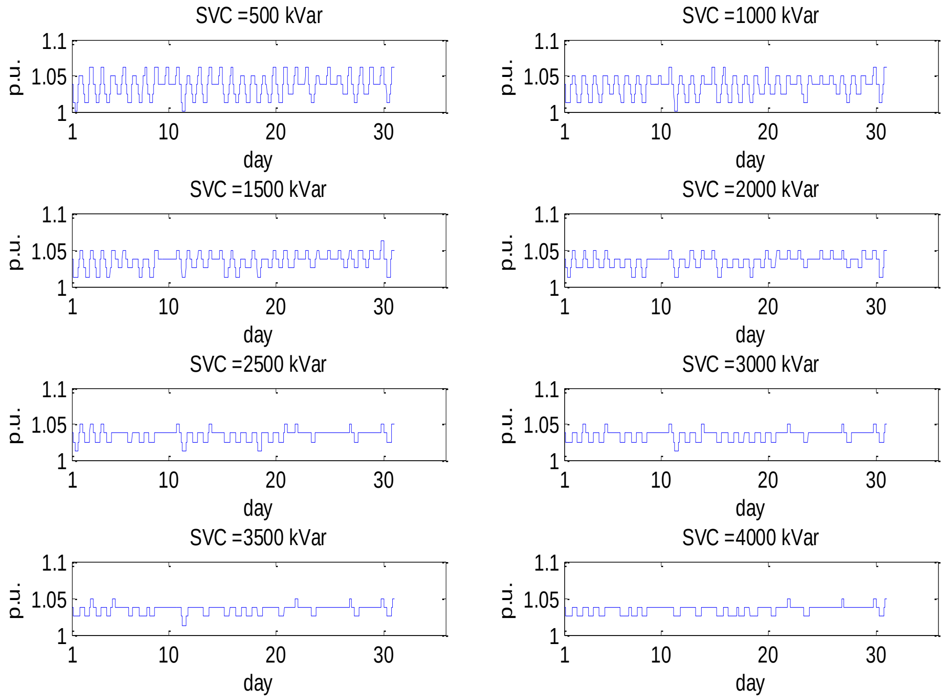

Fig. 4.18 The OLTC operation of the above eight SVC capacity values

Table 11 The OLTC operation number of the eight SVC capacity values

SVC capacity (kVar)	OLTC operation number
500	188
1000	152
1500	119
2000	91
2500	63
3000	55
3500	47
4000	39

The OLTC operation time of the proposed load scheduling method is 38 times (see Table 10 and Fig. 4.16). So the equivalent SVC capacity is 4000 kVar with the similar OLTC operation times.

Chapter 5 Conclusion

This dissertation introduces the research of voltage control method via residential load scheduling in next generation power distribution system. A day-ahead load scheduling and a real-time load rescheduling method are proposed. The conclusion of the whole content is as follows:

Chapter 1 describes the background of the research. First, the developing of power distribution system is introduced. After that, the voltage control issue is described. With the integration of PV and EV, the overvoltage and low voltage violation problem will be more serious in the next generation power distribution system. At last, the research purpose and main content is introduced.

Chapter 2 introduces the system model of this research. Mathematical model of household SLs are built. Then the proposed central CEMS and multi-sub-CEMS model in the distribution system is introduced. These models are the base of realizing the voltage control methods in this research.

Chapter 3 proposes a day-ahead load scheduling method. The purpose is to maximize customers' profit and reduce the voltage violation number of times. The problem is formulated as an optimization problem, and GA is utilized to solve the optimization. The proposed method is validated both on 12-customer and 1800-customer distribution system, and 3 cases are considered in the simulation. Comparing the results among the 3 cases, the proposed method can both maximize customers' profit and reduce the voltage violation times through the load scheduling method.

Chapter 4 introduces the real-time load rescheduling method. In this chapter, a coordinated real-time voltage control of an OLTC and CEMS is proposed. The main objectives of this control are to relieve the stress in the OLTC tap operation using the SLs and to follow the day-ahead schedule as much as possible. The scheduling performed by each sub-CEMS is formulated as a combinatorial nonlinear time-series scheduling optimization problem, which is solved by a sequential search method named voltage ranking-based load combination search algorithm (VRLCS). Besides, reactive power generated by PV inverter is also applied in the overvoltage regulation. The simulation result shows that the reactive power can help suppress the overvoltage greatly while not reducing the active power output. At last, the load rescheduling method is also applied for the low voltage regulation. The result shows that the load rescheduling method can reduce the low voltage violation greatly. At last, the value in voltage regulation of the proposed system is carried out by the equivalent SVC capacity.

With the development of smart grid, DSM is recognized as an important part in power distribution system. The DSM can activate customers' load scheduling to help the power system in the peak shaving and voltage regulation. The load scheduling program in the DSM introduced by this research can be a good supplement for voltage control in next generation distribution systems and may help save a large sum of control device investment.

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Publications related to this research

1. Journal papers:

1-1 Qiangqiang Xie, Ryoichi Hara, Hiroyuki Kita, Eiichi Tanaka, "Coordinated Control of OLTC and Multi-CEMSs for Overvoltage Prevention in Power Distribution System", IEEJ Transactions on Electrical and Electronic Engineering (TEEE B), Accepted, will be published in Sept 2017. (*SCI index*)

1-2 Qiangqiang Xie, Ryoichi Hara, Hiroyuki Kita, Eiichi Tanaka, "A Real-Time Cooperative Overvoltage Prevention Control by A Community Energy Management System", Journal of International Council on Electrical Engineering (JICEE), vol.6, no.1, pp.224–230, 2016.

2. International conference papers:

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