Article

Economic Power Schedule and Transactive Energy through Intelligent Centralized Energy Management System for DC Residential Distribution System

Jingpeng Yue [1,*], Zhijian Hu [1], Chendan Li [2], J. C. Vasquez [2] and Josep M. Guerrero [2]

[1] School of Electrical Engineering, Wuhan University, Wuhan 430072, China; zhijian_hu@163.com
[2] Department of Energy Technology, Aalborg University, Aalborg 9100, Denmark; che@et.aau (C.L.); juq@et.aau.dk (J.C.V.); joz@et.aau.dk (J.M.G.)
* Correspondence: 2015102070024@whu.edu.cn; Tel.: +86-137-1797-6970

Abstract: DC residential distribution system (RDS) consisted by DC living home will be a significant integral part in the future green transmission. Meanwhile, the increasing number of distributed resources and intelligent devices will change the power flow between main grid and demand sides. The utilization of distributed generations (DGs) requires an economic operation, stability, environmentally friendly in the whole DC system. This paper not only presents an optimization schedule and transactive energy (TE) approach through centralized energy management system (CEMS), but a control approach to implement and ensure DG output voltages to various DC buses in DC RDS. Based on data collection, prediction and a certain objection, the expert system in CEMS can work out the optimization schedule, after this, the voltage droop control for steady voltage is aligned with the command of unit power schedule. In this work, a DC RDS is as a case study to demonstrate the process, the RDS is associated with unit economic models, cost minimization objective is proposed to achieve based on real-time electrical price. The results show that the proposed framework and methods will help the targeted DC residential system to reduce the total cost and reach stability and efficiency.

Keywords: optimization schedule; transactive energy; DC residential distributed system; living homes, DC droop control; Centralized energy management system, electrical price

1. Introduction

DC power systems are gaining more and more attention in distributed system and microgrids due to their advantages. In energy supply side, many DGs such as photovoltaics, fuel cells, and batteries present natural DC output. Besides, in the load's side, many appliances such as computers, LED lights, computers, and electric vehicles are in facts natural DC loads[1]–[3]. Obviously, it is ideal to power DC loads with DC supply. Moreover, DC system has the advantages to cope with inherent problems related to AC system, such as synchronization of the distributed generators, three-phase unbalances, inrush currents, reactive-power flow, harmonic currents [4]. Nowadays DC microgrids are found in many places and the development technologies of future intelligent DC microgrids are also being deployed for highly efficient integration of distributed generation and modern electronic loads[5], [6]. In this paper, the distributed system consisted of DC living homes. The smart DC living home has been established at Aalborg University, where the ZigBee communication and remote control are deployed[7].

Smart DC distributed power system, integrated together with DGs, controlled loads, energy storage system (ESS), etc., requires to more and more intelligent, economical operation and stability. As the types of renewable sources penetration and efficient and economical utilization of resources, there is an idea that TE framework needs to considerate in the future power system[8], [9]. The transition and advance communication in microgrid technologies make end-customer participation. TE not only permits a user to respond to economic incentives or market policies but allows residential users to gain economic advantage and save energy through cost cost-effective and

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reliable management solutions[10]. In this sense, the expected whole energy system will be more interactive, intelligent, and flexible. The transactive grid has begun in American, residential consumers can buy and sell solar energy through this scale solar project[11].

Energy management system (EMS) of the distributed system is on given objective and inter-disciplinary topic. The EMS can be implemented by a centralized or decentralized way, either of which has disadvantage and advantage[12][13]. According to special system type, such as commercial, residential or military, proper CEMS can be designed to not a supervisor and control the entire system, but gather and management information, optimize and expert dispatch to achieve the efficient and economical way. But the CEMS also have a disadvantage, for example, the fault of the central unit in the CEMS may cause the breakdown of the whole system. Meanwhile, the decentralized control and management for microgrids and distributed system also have been implemented. In the decentralized management way, the agent technology mainly tends in recent years, a multi-agent system is introduced and described in[14]–[16], the system generally includes database gateway agent, date monitor agent, operator agent, DER gateway agent, schedule agent and another agent. Like the CEMS, some inherent problems of the agent system are facing, such as the voltage and power coordination in the distributed network.

According to the definition by the U.S. Department of Energy (DOE), a distributed power system and microgrid can be delineated as a group of interconnected load and DGs within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid[17]. In conventional power system arrangement, the desired voltage is generally maintained by controlling reactive power. As the DER penetration and operation with grid connected, the using of the converter or inverter is mandatory in DC distributed system. And the voltage stability is a crucial issue in grid arrangement [18]. In DC power system, the regulating converter adjusts the system bus voltage. The converter and inverter are responsible not only for transactive energy between the grid and distributed system but also for voltage stability in the distributed network [19]–[21]. In this sense, the DC voltage droop scheme can be used to inject power to DC buses in the process of control. In this work, we use an adaptive DC droop control to adjust the voltage and align with the real-time power schedule.

Given this above, this work mainly has following work. Firstly, the economic dispatch and ET can be achieved through CEMS that manage the power system of DC living homes. Secondly, the primary voltage droop control of converter can get stability and accuracy level. The rest of the paper is organized as follows. In Section II, the structures of DC RDS consisting of DC living home and CEMS are introduced. Control and implement system are presented in this Section III. Economic optimization analysis for components of the system is in Section IV. A case study demonstrates the economical operation in DC DRS in Section V. Finally, Section VII gives the conclusion and future work.

2. Structures of DC Residential Distributed System(RDS)

The RDS mainly consisting of DC living homes integrate the electrical and information infrastructure, which is shown in Fig. 1. Each living home equips with a smart meter, and interconnection with the main grid, intelligent CEMS and electrical market. Customers can receive power from both renewable energy sources and the external grid. Besides, these operators are also willing to inject extra power into the grid to share through TES. The following introduces the main power framework and CEMS.

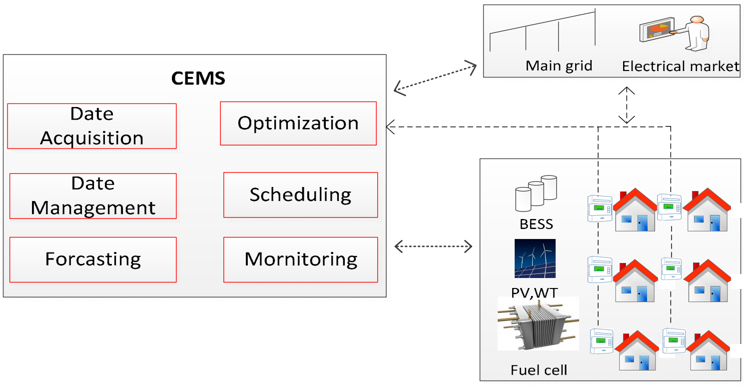

Figure 1. Structure of DC RDS

2.1. Power Architecture of DC RDS

The power system of DC RDS is framed by distributed generators (PV panels, wind turbine, and a fuel cell), energy storage devices (Li-ion battery), converters, DC buses and loads.

(1) Distributed generators: composed of PV panels and wind turbines in series or in parallel. The maximum peak power tracking（MPPT）technology is implemented to emphasize high efficiency in the DC RDS.

(2) Converters: these are responsible for charge and discharge for buses with loads and generations. Unidirectional DC/DC converter is used for connecting PV and DC load with DC buses with different voltage levels, bi-directional DC/DC converter is for connecting BESS with 48 V DC bus. AC/DC converter is used for AC distributed power with DC bus. The DC residential area is connected to the utility grid through a centralized bi-direction converter.

(3) Buses: all system components including DGs, loads, ESS, etc. are connected to multi-voltage lever buses by converters. The 230 V, 48 V, 24 V and 12 V DC buses are deployed in this DC RDS[22].

(4) Energy storage system(ESS): composed of advances in the Li-ion battery technology in parallel or series, which not only be utilized to absorb excessive power and to carry out the way of charging and discharge as the signal from EMS, but has a fast response time following the cooperation control[23][24].

(4) Information system (IS): with aid of the wireless communication and the smart meter is imperative in achieving TE. The DC living home lab in Aalborg is equipped with Zigbee smart device that is flexibility and comfortable for users experience[25].

2.2. Centralized energy management system

In DC residential distribution system, the function of EMS can be implemented in a centralized way. This RDS follows a CEMS similar to the structure for microgrid[26]. The CEMS consist of the central controller and wireless communication that is provided with the relevant information from different meters of actors in this DC system environment. Then, According to the various objectives, CEMS is identified for the real-time optimization to dispatch the DER unit in DC system. In details, the responsible of the CEMS are:

• Collecting and management local information, e.g., load date, power of generation, smart meter dates.

• Forecasting information of DER, e.g., load, the power of WTs, PVs.

• Main Grid information, e.g., real-time electrical price, demand response information.

• Monitoring the whole system, e.g., state of charge of the ESS, security and reliability constraints of the DC residential system.

• The expert system, e.g., optimization algorithms for various objection, constraints and operational limits of units.

• Output variables of the EMS are the reference values of the control system (e.g., output power and/or terminal voltage) for each dispatchable DER.

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3. Control and implement system in the DC system

Apart from the optimization schedule, the DC system is technically suited for providing control reserve allowing tracking the command and short response time.

3.1 Adaptive Droop control in DC distributed power system(network)

A hierarchical approach could adopt for designing for the control system of DC residential system, which is identified: primary, secondary, and tertiary control. Converters control is based on the voltage droop control to share power for DGs and be responsible for tracking DC voltage reference. The secondary control is for removing voltage deviation and reliable operation, the tertiary control is responsible for the economical and coordinated operation and host grid that related to transactive energy control. In this work, we mainly considerate the primary control. PV and WT are preferred to inject maximum power and operated in MTTP mode, however, the output voltages of DERs in common bus should be the priority. The bidirectional and directional converter are mandatory to adaptive the out voltages through adaptive droop loop. The equivalent circuit of voltage droop control for three parallel voltage source converters is shown in Fig. 2.

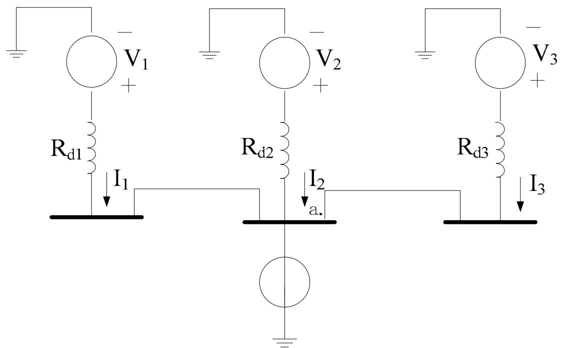

Figure 2. Equivalent circuit of parallel DGs

The Fig. 2 shows the equivalent circuit of three parallel voltage source converters to accomplish current sharing in distributed way. The output voltage reference of every converter should follow voltage droop characteristic defined with virtual impedance. The grid forming converter in this system can be expressed as [13]:

$$v_{o,i} = v_{ref,i} - R_{d,i} \times i_0 \tag{1}$$

$$R_d = 1 / \sum_{i=1}^{n} \frac{1}{R_{d,i}} \tag{2}$$

Where $v_{0,i}$ is the voltage reference of the converter *i*, i_0 is the output current of the converter *i*, $v_{ref,\ i}$ is the reference voltage of the droop circuit, R_d is the virtual impedance value. For the distributed unit *i* connected with bus, the power generated by unit *i* can be written as

$$P_{DG,i} = v_{o,i} \bullet i_{o,i} \tag{3}$$

The droop circuit in DC power system is converters resistance, so the virtual impedance can be considered constraints. As Kirchhoff's current law and (1), (3), in voltage droop circuit can be written as

$$P_{DG,i} = v_{ref,i} \bullet P_{DG,i} / v_{o,i} - R_{d,i} \bullet P_{DG,i} \tag{4}$$

Where $P_{DG,i}$ is the power of dispatchable unite *i* in the network, $v_{ref,i}$ is the reference voltage of various buses, $R_{d,i}$ is the virtual resistance in voltage droop circuit. According to the signal of the real-time power scheduling, we can program primary control by optimizing the adaptive virtual impedances R_d. Assuming ε is the maximum allowed voltage deviation, which is generally ± 5% deviation, R_d and v_{ref} are designed as:

$$v_{ref} = v_n - \varepsilon / 3 \tag{5}$$

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$$R_d = \varepsilon / i_{\max} \tag{6}$$

Where v_n is the output voltage and $i_{\max}$ is the maximum output current. The equations show the equivalent circuit of three parallel voltage source converters. In the processing of schedule, the droop control level adjusts the voltage reference provided to the inner current and voltage control loops. The every bus voltage should follow the output voltage of every converter every defined with virtual impedance.

3.2. Flow chart of schedule and TE

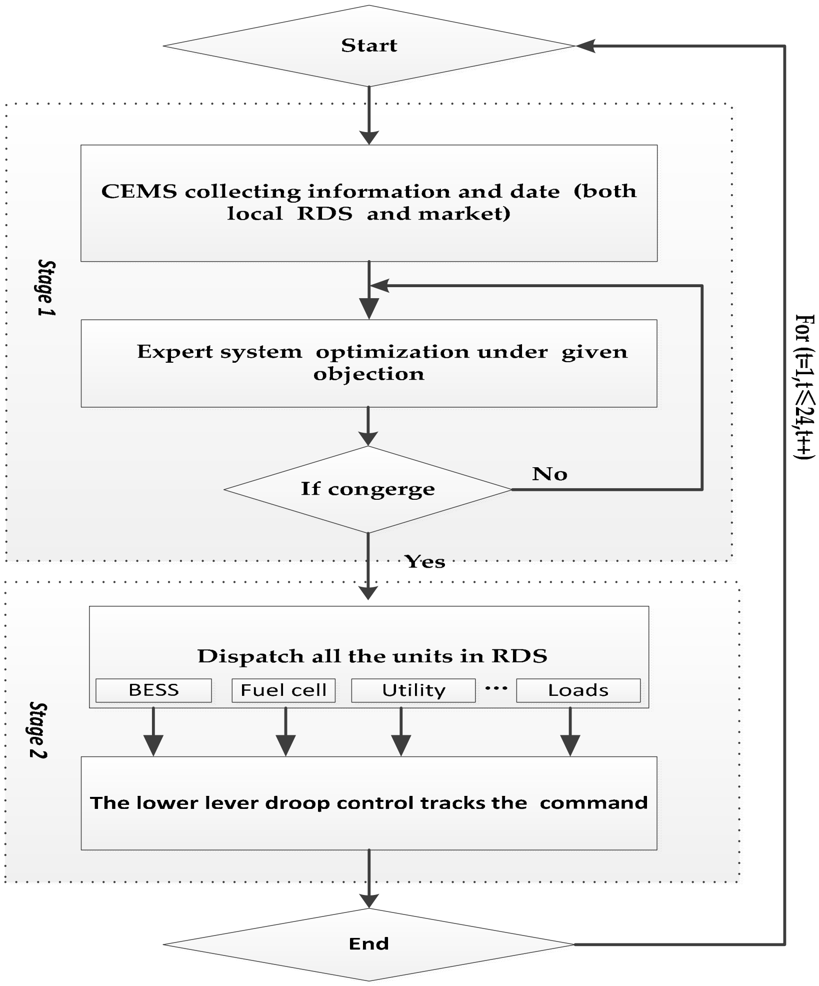

Figure 3. Dispatch mechanism of CEMS

The ESS is core in the process of TE.

The operation of schedule and transaction energy is usually various objection and constraints not only electrical but the environment and economic issues. In this work, we mainly consider the cost minimization of the whole system based on the real-time price from the electrical market.

Based on the power flow of schedule, in order to coordinate the units of the system in a highly efficient way and keep bus voltage stability, the optimization virtual R should be calculated according (1)-(4) for adaptive droop control implement. As the penetration of DER, injection power to the grid may cause reduction or rise in voltage. Some international standards such as IEEE 1547, 2030 define the limits for DC injection[27]. In this work, the bus voltage cannot cause voltage fluctuation greater than ±5%。

4. Optimization for Economic Operation in DC Residential System

4.1. Cost composition in DC system

(1) Cost of utility

With the development of bidirectional communication technology in smart grid, the transactive energy between constraints grid and distributed grid can improve the economic efficiency. In other words, customers not only can buy electrical energy from the utility but also sell energy to main grid base on the transactive mechanism. Based on the real-time price observed from the electrical market, operator of DC residential distribute d system could make real-time demand response and optimization schedule. The cost of utility in a control cycle can be modeled as:

$$C_{utility,i}=\begin{cases} f_{buy}P_{utility}\cdot\Delta t_i, P_{utility}>0 \\ f_{sell}P_{utility}\cdot\Delta t_i, P_{utility}<0 \end{cases} \tag{7}$$

$$C_{utility}^{total}=\sum_{i=1}^{T}C_{utility,i} \tag{8}$$

Where f_{buy} is the real time price from an electrical market, f_{sell} is the electrical price subsidies for power from DC distributed system to grid, $P_{utility}$ is the power between grid to DC distributed system, which is positive when the DC distributed system absorb energy from the grid, and negative when DC distributed system contribute energy to grid. T is the number of optimization intervals, ΔT_i is the length of *i-th* time interval, $C_{utility}^{total}$ is the total utility cost in the whole optimization intervals.

(2) Cost of fuel cell

The generation cost (except renewable generation) can be modeled by the well know quadratic function of output power as (9)[1], so the cost of the fuel in the system can model as (10)

$$C_F=\alpha P_F^2+\beta P_F+\gamma \tag{9}$$

$$C_F^{total}=\sum_{i=1}^{T}((\alpha P_F^2+\beta P_F+\gamma)\cdot\Delta t_i) \tag{10}$$

Where α,β,γ are constants, P_F is the output power of fuel cell. ΔT_i is the length of *i-th* time interval, C_F^{total} is the total fuel cell cost in the whole optimization intervals.

(3) Life loss of BESS

In a conventional way, the energy circulation can influence the life loss of Li battery. Suppose the temperature is constant, the relationship of circulation number *L* and discharge power E_i in *it* follows (11)[28]. When the self-discharge/charge is ignored, the total discharge energy equals to the charging energy in one circulation. In the sense, the life loss in the circulation can be equal to the cost of the BESS. In this work, a cost coefficient is used to build the relationship between the energy circulation and cost of BESS, which is shown in (12) and (13). So the reasonable schedule of charge and discharge power will beneficial to the life of BESS.

$$L=-a\cdot(E_i/E_b)+b \tag{11}$$

$$C_{bess}=\begin{cases} L\cdot p_{bess}\cdot\Delta t_i, p_{bess}\geq 0 \\ L\cdot\left|p_{bess}\right|\cdot\Delta t_i, p_{bess}<0 \end{cases} \tag{12}$$

$$C_{bess}^{total}=\sum_{i=1}^{T}C_{bess,i} \tag{13}$$

Where E_b is the rated capacity of *Li* storage batteries, thea and b constant are both converters. When the battery is charging, the value of P_{bess} is positive, or else that is negative. The costs in one period are the sum of *i-th*.

(4) Renewable energy cost

Support the customers of the DC residential are the investor of the RES, the cost of REW is free and considered zero. To maximize the REW, the design of the control including MTTP and strategy of operation are economic.

(5) Power Loss

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The power loss depends on specific cases and detailed information of the system, e.g., the length of cables, various converters, devices and generators. As the control order is implemented by the converters, which are the mainly interdisciplinary of power losses, we can consider the power losses took place in converters devices to evaluating the power loss of the DC residential distributed system, The maximum design value allowed is usually as unit as 10% rating in microgrids[1]. The power losses can be written as following：

$$C_{loss}^{total} = f_{buy} \sum_{i=1}^{T} \eta_{ic} \cdot P_{ic} \cdot \Delta t_i \tag{14}$$

Where the η_{ic} is efficient of the converters, P_{ic} is the output power of converters.

4.2. *Objective function*

The objection of this study is to minimize the total operation cost in 24 hours based on the real-time electrical price, which can be written as:

$$\min C_{system}^{total} = f(C_{utility}^{total} + C_{F}^{total} + C_{loss}^{total} + C_{bess}^{total}) \tag{15}$$

Where the total cost can be calculated through (8), (10), (13) and (14), which is a nonlinear equation.

4.3. *Constrains*

Constraints include each unit and the whole system constraint.

(1) system constrains

According to the power balance of the system, constrains can be written as:

$$P_{pv} + P_{wt} + P_{utility} + P_F - P_{ess} - P_{load} - P_{loss} = 0 \tag{16}$$

(2) BESS charge/discharge strategy and constraints

Reasonable scheduling of charging and discharging power of energy storage system (ESS) is beneficial to extending the life of ESS. Assume the discharge capacity equal the charge capacity.

SOC/ charge discharge

$$E_{t+1} = E_t + \eta_c P_{bss,t} \cdot \Delta T \tag{17}$$

$$E_{t+1} = E_t + P_{bss,t} / \eta_d \cdot \Delta T \tag{18}$$

$$\sum_{t=t_a}^{t=t_{b-1}} E_t < E_{t+1} < 0.8 E_{\max} \tag{19}$$

$$-0.8(E_{\max} - \sum_{t=t_a}^{t=t_{b-1}} P_t \times 1_t) / \Delta T < P_{t_b} < 0.8(E_{\max} - \sum_{t=t_a}^{t=t_{b-1}} P_t \times 1_t) / \Delta T \tag{20}$$

(3) Other constraints

Each unit should keep their capacity limits, the utility and fuel cell can be expressed as following inequity constrains:

$$P_{utility,\min} < P_{utility,i} < P_{utility,\max} \tag{21}$$

$$0 < P_{F,i} < P_{F,\max} \tag{22}$$

The optimization schedule problem is mixed integer and non-linear formulation program, so the methodology of solving can use various inequality optimization in the expert system. In constraints system, the optimization result achieves after the power flow converges. In this work, we solve the problem using the sequential quadratic programming to make a lot of iterations to find the results of the goal.

5. Case study

In this section, we present a 6-bus DC residential system model as shown in Fig. 4 to verify the proposed method. The bus voltage standard includes 230 V, 48 V, 24 V and 12 V. Meanwhile, the

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data of units will be collected and processed through CEMS, which also command the schedule and control.

The prediction generation of WTs and PVs constraints in the appendix Table 1 with the plot is given in Fig. 5. Take a 24 hours real time electrical price from Nord pool electrical market as a case, which constraints in appendix Table 2 with the plot given in Fig. 6. For the minimizing cost objection and the constraints of units real-time in appendix Table 3, the optimization method of a sequential quadratic program makes a lot of iterations to find the optimization results for cost minimization. The optimized power schedule results are shown in Fig. 5. The schedule contains the charge/discharge of ESS and power flow of fuel cell and utility, and also satisfied the constraints. The whole day economic consumption is shown in Fig. 6. The comparison shows that the total cost has been reduced by optimally schedule the resources.

The CEMS is responsible for computing the optimized schedule and implement. In daily control operation, consideration of the voltage stability, the adaptive VR for converters of ESS, utility and fuel cell constraints are shown in Fig. 10. Meanwhile, Fig. 11 shows that the voltage vacillation is within the allowable range. The results show that DC RDS can reach the stability and economical level, which will be not the only benefit of customers but also grid.

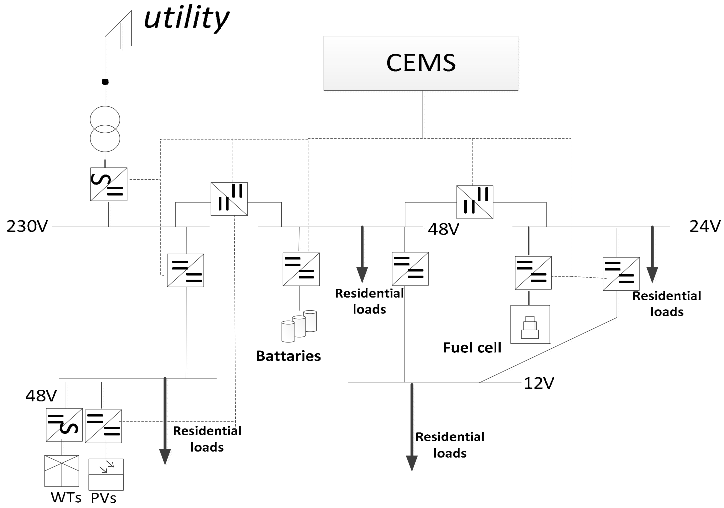

Figure 4. Structure of the 6-bus distributed residential power system

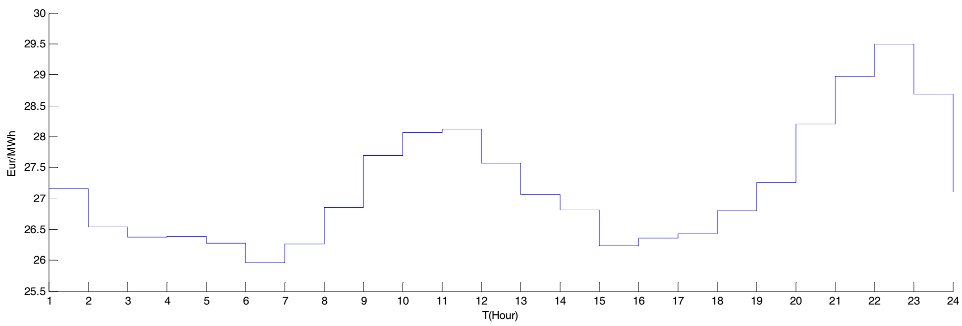

Figure 5. Real-time price from Nord pool Market

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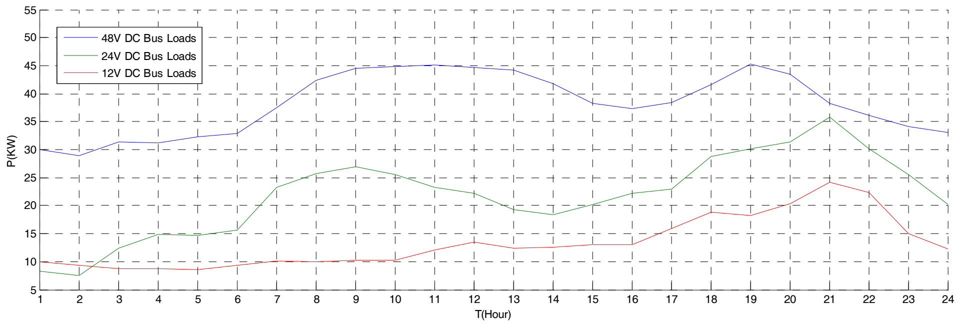

Figure 6. Loads of DC bus in the residential system

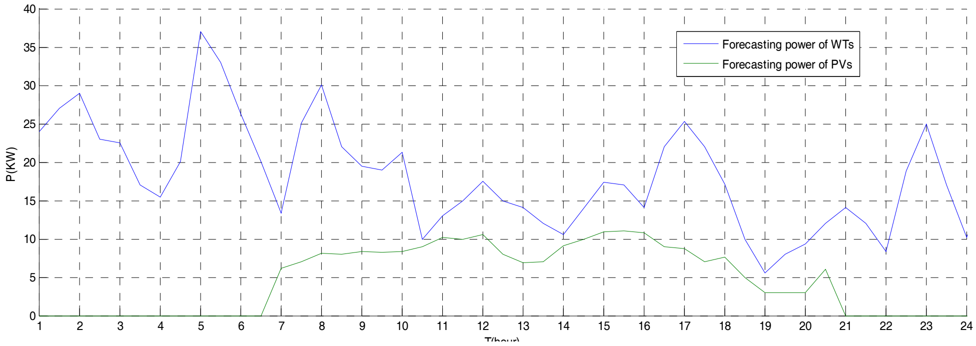

Figure 7. The DGs power in the DC residential system

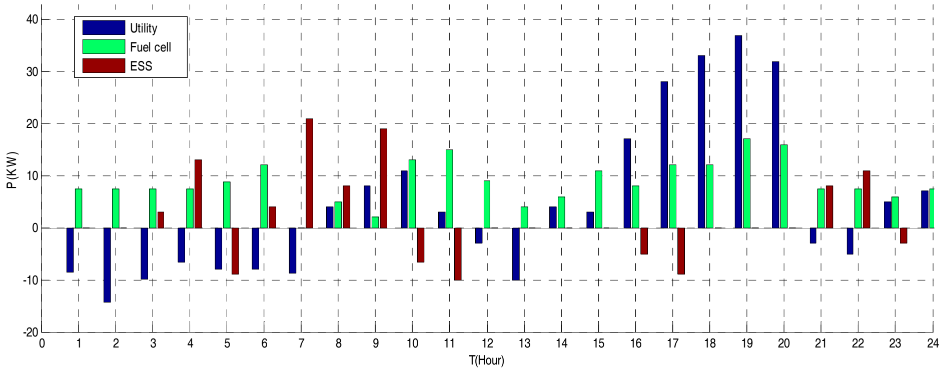

Figure 8. The hourly schedule of units

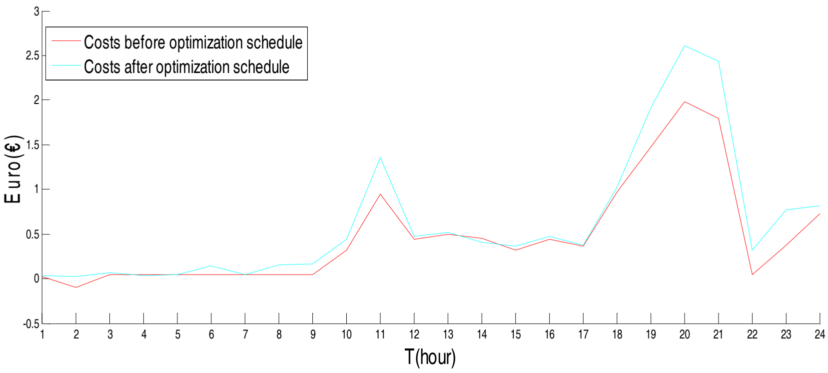

Figure 9. The costs compare to DC residential system

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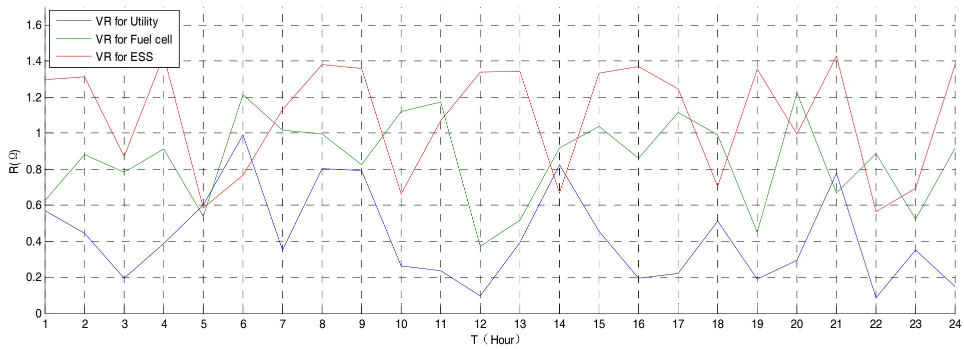

Figure 10. The VR Implement of converters in droop control

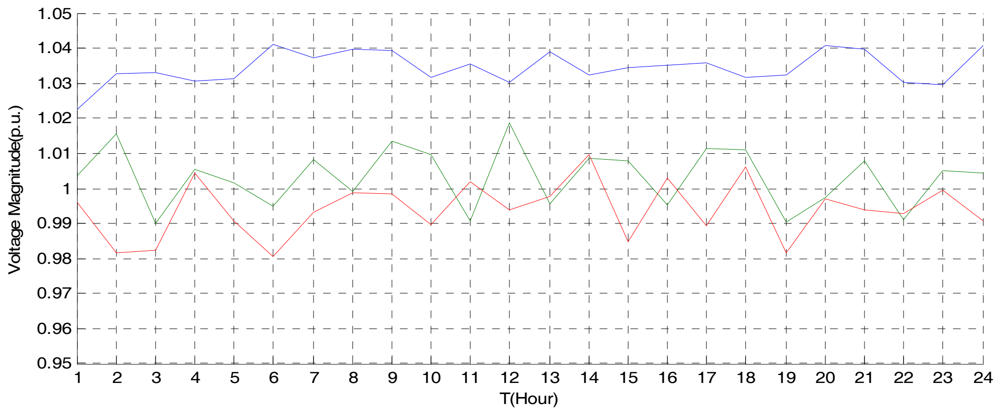

Figure 11. The voltage deviation of droop units

6. Conclusion and future work

As a promising power system, RDS consisting of DC living homes can be managed through CEMS, which is responsible to collected date, predicted, optimizing, control, etc. This work presents a processing of economical schedule and TE with main grid. The work mainly includes economical schedule and stability operation, the mathematic models of main components in this DC power system can be formulated to optimize the power schedule for the objection of cost minimization based on the real-time electrical price, and the results show the optimized hourly power schedule which can reduce the total cost. Meanwhile, a droop control can track the command and control the converters voltage of main units. In the daily schedule processing, the voltage variation is in the keep in stable range, which is benefit to the whole system stability.

In following-up, the precise adjustment of bus voltage and power flow will be evaluated. And the distributed energy management system will be compared with the CEMS. The work will also track to several contents. For example, the thermal and controlled loads will be considered, the optimizing schedule of electrical vehicle in DC system, the resources of DC RDS can also participate in bidding in the competitive electrical market.

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Author Contributions: Jingpeng Yue carried out the main research tasks and write the manuscript; Zhijian Hu conceived and designed the model; Chandan Li provide the data and modify the model; Vasquez, J.C and Josep M.Guerrero promoted the results.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Appendix

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The load data of DC bus and the generation data of distributed renewable generation are collected from OpenEI. The real-time price is collected from Nord pool.

Table 1 Load and Renewable Generators (kW)

Time	Load(48V)	Load(24V)	Load(12V)	WT	PV
00-01	30.1	8.3	10	24	0
01-02	28.5	7.4	9.4	29	0
02-03	31.9	12.6	8.7	22.55	0
03-04	32.2	31.7	8.6	15.43	0
04-05	33.4	14.9	8.3	37.05	0
05-06	33.9	15.5	9.2	26.22	0
06-07	37.2	24.3	10.1	13.34	6.12
07-08	42.2	25.8	10.1	30.06	8.09
08-09	44.8	27.1	10.5	19.4	8.33
09-10	45	26	10.8	21.32	8.4
10-11	45.2	23.7	13.8	0.33	10.23
11-12	44.6	24	14.2	17.56	10.57
12-13	43.9	19.6	13.8	14.03	6.88
13-14	42	18	14.1	10.53	9.06
14-15	38	20	14.4	17.32	10.89
15-16	37.3	23.3	14.8	14.06	10.75
16-17	38.2	24	15.4	25.3	8.77
17-18	42.8	28.7	19.3	17.15	7.65
18-19	45	30.3	18.8	5.5	3.03
19-20	43.9	32.4	20.2	9.35	2.98
20-21	38.8	35.2	28.6	14.09	0
21-22	36.6	30.1	23.4	8.33	0
22-23	34.7	25.1	15	24.9	0
23-24	33.3	20.3	13	10.23	0

Table 2 Real-Time Electrical Price from Nord POOL (eur/MWh)

Time	**00-01**	**01-02**	**02-03**	**03-04**	**04-05**	**05-06**	**06-07**	**07-08**	**08-09**	**09-10**	**10-11**	**11-12**
Price	27.16	26.54	26.37	26.39	26.28	25.96	26.27	26.85	27.69	28.06	28.12	27.57

Time	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
price	27.06	26.81	26.23	26.36	26.43	26.8	27.26	28.2	28.97	29.5	28.68	27.1

Table 3 Capacity Limits of Units

Controlled units	**Constraint**
Utility	(-50,50)
ESS	(-40,40)
Fuel cell	(0, 50)

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