Real-Time Generation Dispatch and Communication Architecture of Smart Grid with Renewable Energy

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***Abstract*—**Since renewable energies have been and will be massively integrated, electrical power grids require more refined generation dispatch modes and smarter communication methods. In this paper, the real-time generation dispatch and communication architecture of smart grid with renewable energy are studied. Firstly, the technical characteristics and application background of smart grid communication network are introduced. Then, according to the defined candidate model of communication information and the related international standards available to the model, a real-time generation dispatch model, suitable communication method and its simulation environment based on IEC 61850 are established, and adopting them can help to optimize the economical operation point of conventional units and ensure the utility rate of renewable energy. Finally, the proposed generation dispatch model was implemented using MATLAB to estimate the 10 unit test system with a wind farm. From the simulation results, the suitability and availability of the studied generation dispatch model can be proved well.

***Index Terms*—**smart grid ; renewable energy; real-time dispatch; communication architecture; IEC 61850

I. Introduction

Although there is no standard global definition, the European Technology Platform-Smart Grids [1], [2] defines Smart Grids as electricity networks that can intelligently integrate behavior and actions of generators and consumers connected to it, in order to efficiently deliver sustainable, economic and secure electricity supplies. Historically, the industry has been driven from the production and supplier side where very large base load plants have maintained enough supply to handle the normal requirements with excess capacity available on demand. Recently, interest in renewable energy has greatly increased leading to more wind farms and solar plants[3], [4]. However, renewable energy generations are normally non stationary, which result in their uncertainty and intermittence output, and it is very difficult to forecast them precisely. For the sake of controlling the entire power grid flexibly and exactly, studying an advanced power grid dispatch method[5]-[7] and adopting a communication network scheme with high performance [8]-[11] are undoubtedly very meaningful.

For a power system where its applied renewable sources' generation capacities are larger, it is a challenge to implement the real-time power balance. Real-time dispatch (RTD) that directly communicates with automatic generation control (AGC) by providing the most economic dispatch for the available on-line units, will play an important role in smart grid. To achieve the effect of RTD and enhance the look ahead ability of the system, we must take into account the prediction information of intermittent generation power, such as wind speed, wind direction, pressure, temperature and other Numerical Weather Prediction (NWP) data, as well as some physical data [12]. Accordingly, RTD will heavily depend on flexible information technology, and real-time two-way communications are the basic guarantee platform.

In fact, there is an urgent need to establish protocols and standards for the smart grid. The NIST report (Phase I) provides a conceptual reference model for the smart grid [13]-[16]. This career is still under the process of research and development, but has been expected to realize the following goals:

- Power grid will support a wide-range of distributed power sources connection. The grid makes all kinds of generation devices and energy storage system seamless integrated, which should be easy for connection and operation.
- Produce new electricity products, services, and establish new electricity market. Power grid supports the secondary electricity market (real-time dispatch).
- Optimize the operation of power system. The grid should get improved load factor and reduce line loss; make the existing system more powerful; utilize efficient and optimized tools; work flow management and outage management; facilitate system operation and maintenance.

Based on the above mentioned technical background, in this paper, the real-time generation dispatch and communication architecture of smart grid with renewable energy are studied. According to the defined candidate model of communication information and the related international standards available to the model, a real-time generation dispatch model, suitable communication method and its simulation environment based on IEC

Manuscript received May 10, 2013; revised July 25, 2013.
This work was supported in part by National Natural Science Foundation of China (51190104) and National Science and Technology Support Program of China (2013BAA02B02).
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doi:10.12720/jcm.8.8.497-504

61850 are established. In addition, the proposed generation dispatch model was implemented using MATLAB, so as to estimate the 10 unit test system with a wind farm.

II. Communication Architecture for Renewable Energies

A. Information Structure

One of the basic requirements for the successful realization of real-time generation dispatch is having unified communications architecture towards renewable energies. This can be realized using IEC 61850 [17]-[21] communication standard. IEC 61850 information modeling is based on the hierarchical object-oriented structuring of process data. The generic data structure is defined in the original IEC 61850 parts and standard extensions, such as IEC 61850-7-420, assign internationally valid names to real-world data.

The architecture of the structured process data, based on IEC 61850 modeling rules, is divided into several levels as shown in Fig. 1. The information structure is the base for single-data-source integration, and power information system incorporation, with the target of establishing a unified data exchanging and sharing mechanism by means of a standardized information depiction, and a unified data exchanging platform and access.

B. Description Model of Information

Due to the challenge of mass data from a complicated application environment, XML is adopted for describing integration data in smart grid network. XML is a flexible data model language, with self-described feature, which makes it perfect to represent both data and content, since it allows the user or application to add meta-data to state background information. XML can break the block between data and its content; and enable seamless connection among multi data sources. XML stimulates the integration and analysis based on multi-heterogeneous data source.

C. Information Model for Renewable Energies

The IEC 61850 process data class hierarchy enables the generation of function-based device models which easily distinguish key supervision and control endpoints. As shown in Fig. 2, an information model suitable for renewable energies was applied in this paper [22]. The model is developed according to IEC 61850 modeling rules and definitions. A list of LN(Logical Node) abbreviations used in renewable energy model can be found in Appendix A. A detailed description of each of LNs and related data-set is beyond the scope of this paper and can be found in [18], [23], [24]. The model integrates a wind power plant, and a photovoltaic array. Fig. 2 shows that the IEC 61850 provides generic and adjustable modeling capabilities required by diverse and variable renewable energy optimization objectives.

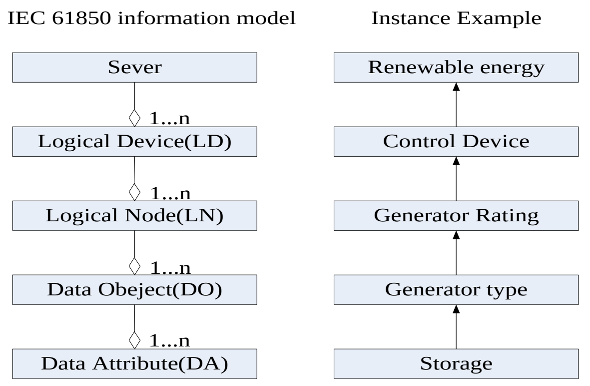

Figure 1. IEC 61850 information model classes and exemplary instances.

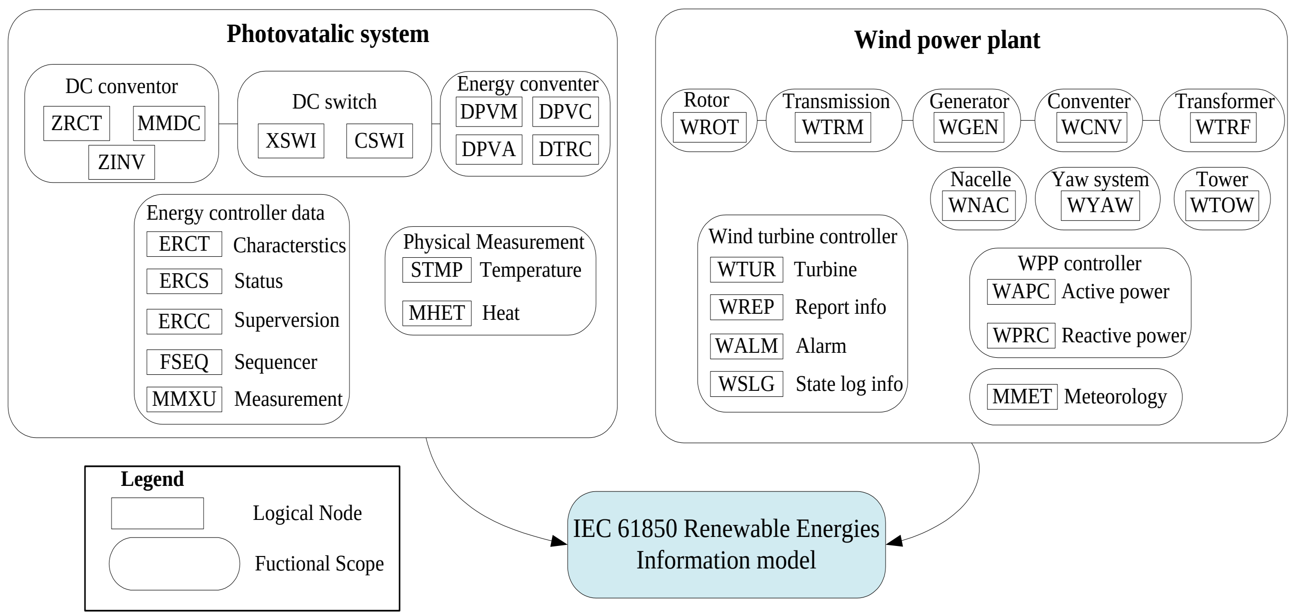

Figure 2. Renewable energies information model based on IEC 61850.

D. *Abstract Communication Service Interface*

The Abstract Communication Service Interface (ACSI) is a novel paradigm, introduced by IEC 61850, for describing data exchange procedures and requirements [17]. ACSI model classes define standardized information services for IEC 61850 devices. The ASCI model classes required for vertical information exchange are those enabling:

- Creation of application connection with a device (the Application association model).
- Browsing and editing device information model (the Server/LD/LN/DO/DS models).
- Changing active settings group (the Setting-Group-Control-Block model).

These ACSI model classes can be used as standardized information interfaces for renewable energies. Thus, any IEC 61850 enabled client software can take full advantage of renewable energy remote control.

III Real-Time Generation Dispatch Based on IEC 61850 Communication Standard

A. *Simulation Environment*

For the purpose of demonstrating the proposed solution, a specific co-simulation environment is created as shown in Fig. 3. It is based on DIgSILENT Power Factory and MATLAB optimization toolbox [25], [26], and it can be considered as a high-level service and intermediary application responsible for managing co-simulation environment. Besides, a 10 units power network and a wind farm including 56 wind turbines whose total capacity is 140MW, are imitated in DIgSILENT Power Factory [27]. It should be pointed out that, the simulated wind turbines are according to IEC61850 information models.

First discrete simulation step results (current units and wind farm active power) are provided to intermediary application through DIgSILENT's Shared Memory Interface. On one side intermediary application communicates with DIgSILENT and on the other side provides Web client interface for communicating with MATLAB over the Local Area Network. Communication between Web client (intermediary application's interface) and Web server (wrapped MATLAB's engine) is done over XML-based Web Services. These set points represent second simulation step results which are provided to intermediary application as response from Web server.

Real world implementation requires IEC 61850 enabled generators as distributed standalone devices and existence of high-level service (e.g., real-time dispatch service or weather data services) as shown in Fig. 3.

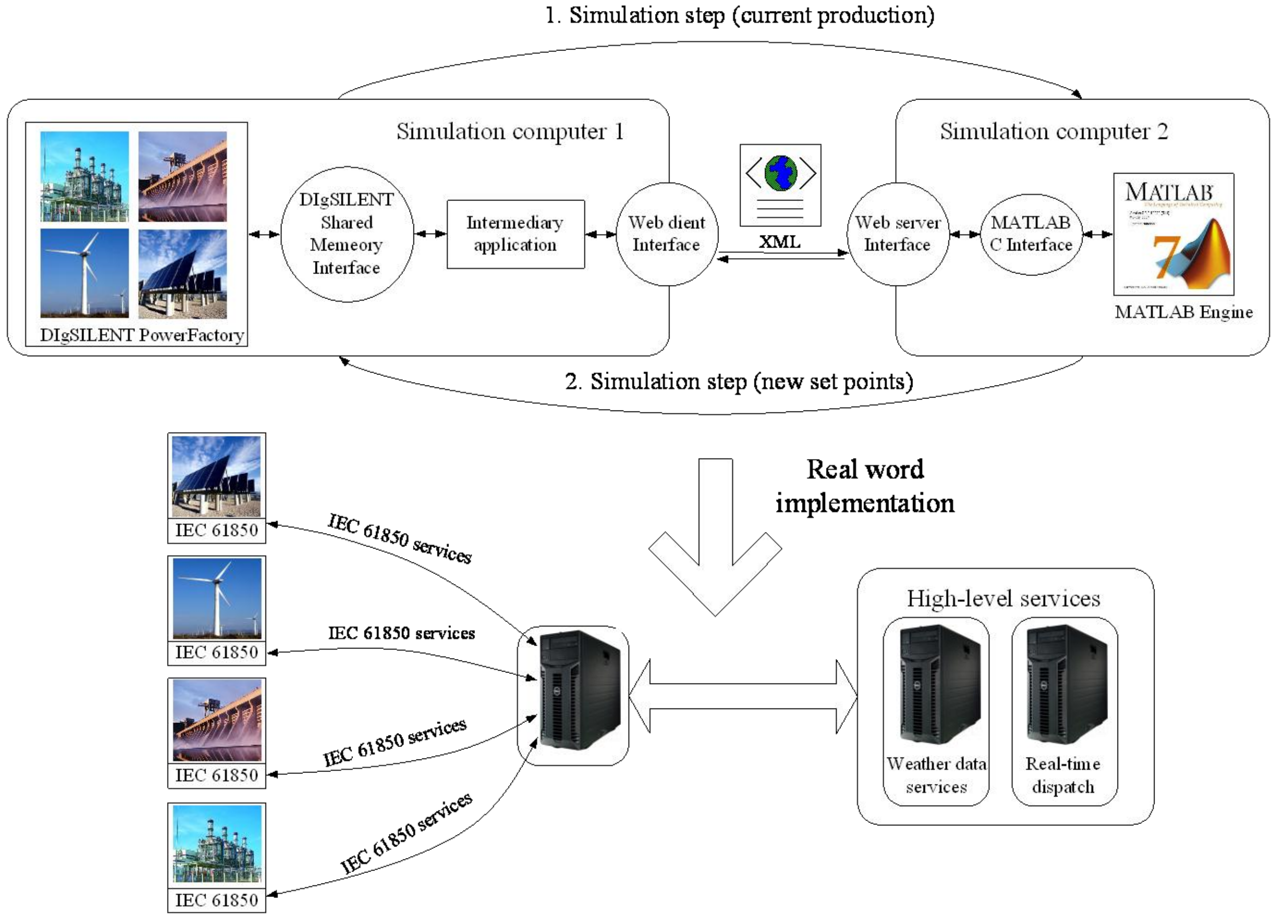

Figure 3. Simulation environment and real world implementation concept.

B. Mathematical Formulation for Real-Time Dispatch

Real-time dispatch is an ahead scheduling procedure for optimizing the economical operation point of smart grid for the next dispatch period. Since the deviation from the predictive operation situation is always existing, real-time dispatch needs to correct the operation point continually. In real-time dispatch, we also have to deal with the possible circumstance that the power system is close to its security regions edge. Consequently, on the one hand, we should let the system absorbing imbalance power, and on the other hand, some security constraints must be considered.

Owing to the requirement of smart grid for energy conservation and emission reduction, the bottom of a feasible dispatch method is maximizing utilization of renewable energy and minimizing operation cost, and in this paper, in consideration of the two factors, a comprehensive scheduling decision making is proposed.

The total incremental operation cost can be expressed as:

$$f_1 = \sum_{i=1}^{N_G} a_i \Delta p_{G_i,t}{}^2 + (2a_i p_{G_i,t\text{-}1} + b_i)\Delta p_{G_i,t} \tag{1}$$

where a_i and b_i are the cost coefficients of the i^{th} conventional unit, which can be found from the input–output curves and are dependent on the particular type of the used fuel, N_G is the number of conventional units, $p_{G_i,t\text{-}1}$ is the current active power in MW, $\Delta p_{G_i,t}$ is the decision variable of the incremental active power in MW.

Based on the latest prediction production from the power plants, the utilization of renewable energy can be calculated as:

$$f_2 = p_{RN,t}^{\mathrm{ust}} - p_{RN,t} \tag{2}$$

where $p_{RN,t}^{\mathrm{ust}}$ is the latest prediction production of renewable energy in MW, $p_{RN,t}$ is the decision variable of renewable energy output in MW.

The penalty factor, ω is set to coordinate the relations between f_1 and f_2. The objective function of the studied RTD is defined as:

$$\min f = f_1 + \omega f_2 \tag{3}$$

According to $p_{RN,t}^{\mathrm{ust}}$ and the latest load forecast value $p_{L,\ t}^{latest}$, the power balance constraint can be described as :

$$\sum_{i=1}^{N_G} (p_{G_i,t\text{-}1} + \Delta p_{G_i,\ t}) + p_{RN,t} - p_{L,\ t}^{latest} = 0 \tag{4}$$

For different power generation units, their lower and upper generation thresholds, as well as ramp up and ramp down limits will be distinguishing from each other.

$$p_{G_i \min} \le p_{G_i,\ t} \le p_{G_i \max},\ \forall i \tag{5}$$

$$\Delta p_{G_i,\ dn} \le p_{G_i,\ t} - p_{G_i,\ t-1} \le \Delta p_{G_i,\ up},\ \ \forall i \tag{6}$$

$$0 \le p_{RN,t} \le p_{RN,t}^{\mathrm{ust}} \tag{7}$$

where $p_{G_i \max}$ and $p_{G_i \min}$ are the lower and upper limits respectively, $\Delta p_{G_i,\ up}$ and $\Delta p_{G_i,\ dn}$ are ramp-up and ramp-down rate limits respectively.

When a lot of renewable energy generators are installed into a power grid, an additional up and down spinning reserve capacity should be scheduled, to reduce the probability of load shedding and enhance the utilization rate of the renewable energies. The corresponding constraints are given by

$$\sum_{i=1}^{N_G} U_{i,\ t} \ge p_{L,\ t}^{latest} \times L_{\mathrm{u}}\% + p_{RN,t}^{\mathrm{ust}} \times w_{\mathrm{u}}\%,\ \ \forall i \tag{8}$$

$$\sum_{i=1}^{N_G} D_{i,\ t} \ge p_{L,\ t}^{latest} \times L_{\mathrm{d}}\% + p_{RN,t}^{\mathrm{ust}} \times w_{\mathrm{d}}\%,\ \ \forall i \tag{9}$$

where $L_{\mathrm{u}}\%$ and $w_{\mathrm{u}}\%$ are coefficients of up spinning reserve demand, $L_{\mathrm{d}}\%$ and $w_{\mathrm{d}}\%$ are coefficients of down spinning reserve demand, $U_{i,\ t}$ and $D_{i,\ t}$ represent the up and down spinning reserve capacity.

For security consideration, the power flow limit of some important transmission sections can be written as:

$$\sum_{RN \in \Omega_m} \delta_{RN,m} p_{RN,\ t} + \sum_{i \in \Omega_m} \rho_{m,i} p_{G_i,\ t} \le \overline{S_m},\ \ \forall m \tag{10}$$

where Ω_m represents the units set of the m^{th} transmission section, $\rho_{m,i}$ and $\delta_{RN,m}$ respectively represent the active power sensitivities of the conventional unit and renewable energy to the m^{th} transmission section, and $\overline{S_m}$ is the power flow limit.

On the basis of the above equations, the RTD problem can be described as the following quadratic programming form with linear constraints:

$$\begin{aligned} &\min\ \boldsymbol{f}(\boldsymbol{x}) = \frac{1}{2}\boldsymbol{x}^{\mathrm{T}}\boldsymbol{H}\boldsymbol{x} + \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x} \\ &\text{subject to}\ \ \boldsymbol{h}(\boldsymbol{x}) = \boldsymbol{0}\ ,\ \underline{\boldsymbol{g}} \le \boldsymbol{g}(\boldsymbol{x}) \le \overline{\boldsymbol{g}} \end{aligned} \tag{11}$$

where $\boldsymbol{H}$ is a positive semi-definite matrix of the quadratic coefficient of the objective function, $\boldsymbol{c}$ is the coefficient of one degree term of the objective function, $\boldsymbol{x}$ represents the decision vector, $\boldsymbol{h}(\boldsymbol{x})$ represents the equality constraints, $\boldsymbol{g}(\boldsymbol{x})$ represents the inequality constraints, $\overline{\boldsymbol{g}}$ and $\underline{\boldsymbol{g}}$ represent the upper and lower limits of $\boldsymbol{g}(\boldsymbol{x})$, respectively.

IV. Simulation Analysis

To estimate of the proposed real-time generation dispatch model's availability and suitability, the simulation analysis was performed. A prime-dual affine scaling interior point method was utilized to achieve the optimal solution in MATLAB.

The latest forecast load and the conventional units data can be indicated in Table I and Table II.

TABLE I. THE LATEST LOAD FORECAST DATA

Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)
1	1096	9	1984	17	1540
2	1170	10	2132	18	1688
3	1318	11	2206	19	1836
4	1466	12	2280	20	2132
5	1540	13	2132	21	1984
6	1688	14	1984	22	1688
7	1762	15	1836	23	1392
8	1836	16	1614	24	1244

TABLE II. CONVENTIONAL UNITS DATA

Unit	$p_{Gi\max}$ (MW)	$p_{Gi\min}$ (MW)	a_i (\$ /MW^2)	b_i (\$ /MW)	$\Delta p_{G_i,\ up}$ (MW/min)	$\Delta p_{G_i,\ dn}$ (MW/min)
1	470	150	0.043	21.60	4.70	-4.70
2	460	135	0.063	21.05	4.60	-4.60
3	340	73	0.039	20.80	3.80	-3.80
4	300	60	0.070	23.90	3.53	-3.53
5	260	57	0.056	17.87	3.70	-3.70
6	243	73	0.079	21.62	3.33	-3.33
7	130	20	0.211	16.51	2.00	-2.00
8	120	15	0.480	23.23	1.20	-1.20
9	80	10	1.091	19.58	0.80	-0.80
10	55	55	0.951	22.54	0.55	-0.55

According to the weather data, we can forecast the output of the renewable energy (taking the wind farm for an example) using ultra-short-term forecast technology. As shown in Fig. 4, it indicates the one-day output characteristics of the wind power based on the day-ahead forecast data (curve 1), obtained ultra-short-term forecast data (curve 2) and measured output data (curve 3). It can be observed that, the curve 1 has significantly underestimated the wind power's actual output, and then will cause wind spillage and reduce its utilization rate. On the whole, the dynamic trend of the curve 2 is more similar to that of the curve 3. The average error of the curve 2 is approximatively 6.03%, matching with the measured values better.

During the simulation process, starting from the 30th period (15mins/interval), the proposed real-time dispatch algorithm was performed. The parameter settings can be shown in Table III. The studied transmission section is composed of the conventional unit 1 and the wind farm. The power flow limit is set as [-500 MW, 500 MW].

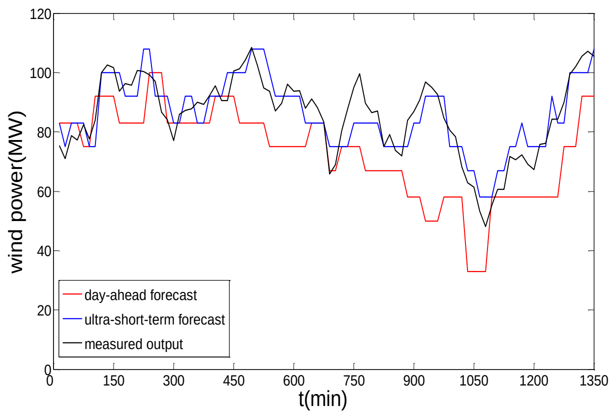

Figure 4. Curves of wind power forecast and measured output

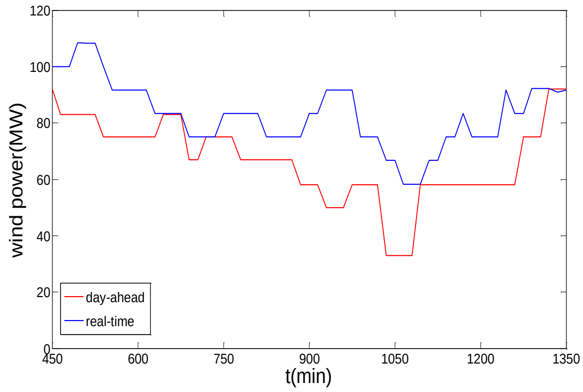

Figure 5. Curves of wind power *output scheduled*

Compared with the measured output, the average deviation of the day-ahead scheduled wind power is 17.386 MW, and after using the proposed real-time dispatch model, the deviation can reduce to 6.321MW. As a result, the RTD based on the ultra-short-term forecast data has better ability to track the fluctuations in the wind power. Therefore, the power system could absorb an additional wind power with the capacity of 15.342MW in each period, and it could be observed in Fig. 5. The detailed data could be found in Appendix B.

TABLE III. OBJECTIVE FUNCTION VALUES

	Total cost (\$)	f_1 (\$)	f_2 (\$)	f (\$)
Day-ahead	4944791	0.0000	/	/
Real-time	4893118	-51673	31262	-20411

Along with more absorption of wind power, the operation cost of the system reduces obviously. Appendix C shows the conventional units' optimization outputs in 10 periods, under the conditions that adopting the day-ahead (DA) and real-time schedules, and \$1074.47 can be saved per a period. The optimization results of the objective function were given in Table 4 when the real-time dispatch algorithm was performed all day long. It can be found that, the cost of \$ 51,673 can be totally saved.

From Fig. 6, the constraints of the active power flow limit at the transmission section are satisfied. Fig. 7 and Fig. 8 show the power output curves of the conventional units 1-10 before and after using the proposed real-time dispatch model. It can be clearly watched that the units' operation trajectories have been corrected.

The proposed real-time dispatch algorithm's average computation time is about 0.74s, and it can meet the related operation requirement. Fig. 9 shows the objective function's convergence trajectory in the case of changing the computation iteration. It can be seen that, the objective function is very close to the final stable value when the computation iteration is set as 8. Fig. 10 shows the duality gap's convergent tendency under increasing the computation iteration. From the above simulation results, the algorithm's convergence and computational efficiency can be testified well.

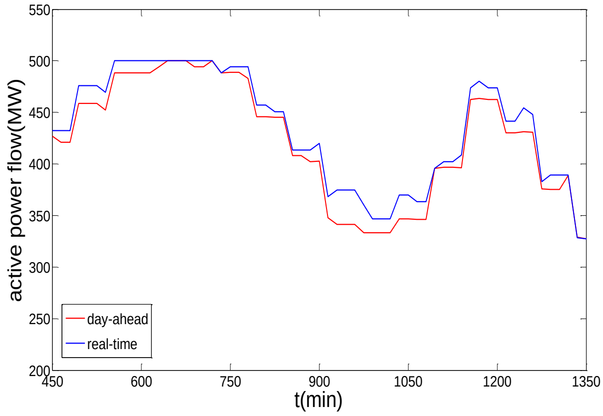

Figure 6. Curves of active power flow at the transmission section

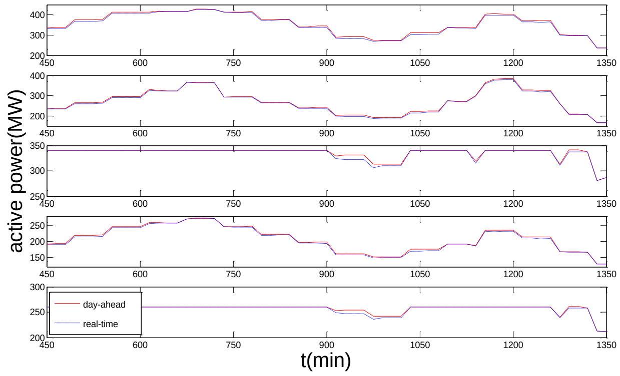

Figure 7. Curves of active power output scheduled of unit 1-5

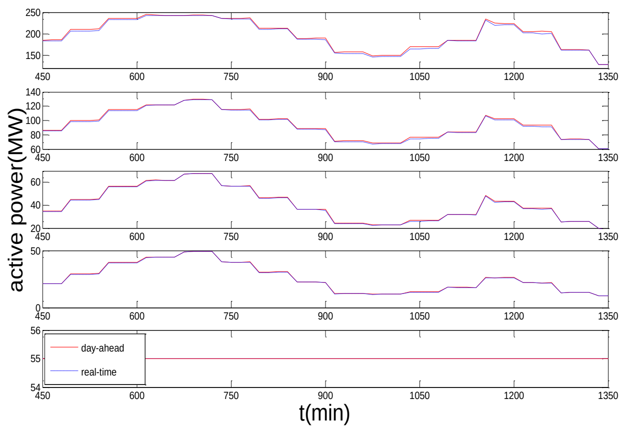

Figure 8. Curves of active power output scheduled of unit 6-10

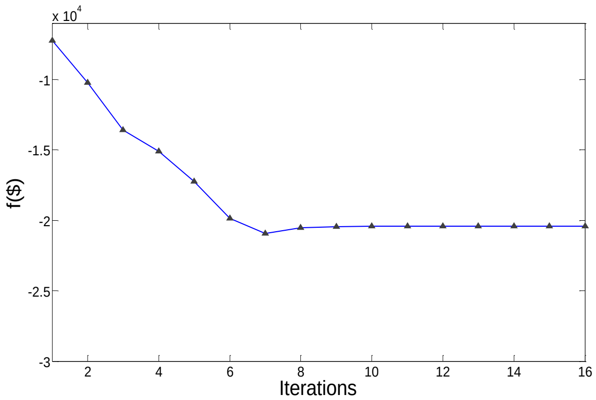

Figure 9. Object function convergent tendency of 10 units

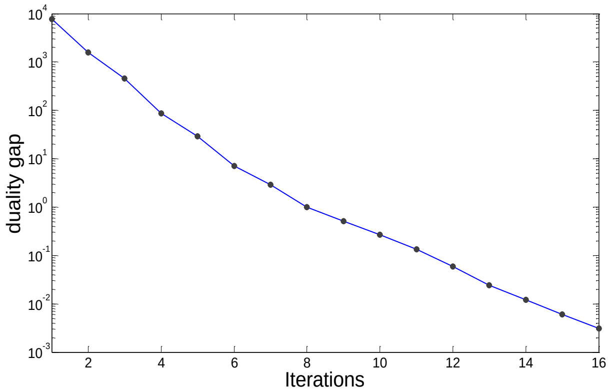

Figure 10. Convergent tendency of 10 units

Logical node	IEC 61850 function
CSWI	Switch controller
DPVA	PV Array characteristics
DPVC	PV Array controller
DPVM	PV Module ratings
ERCC	renewable energy supervisory control
ERCS	renewable energy controller status
ERCT	renewable energy controller characteristics
DTRC	Tracking controller
FSEQ	Sequencer
MHET	Heat measured values
MMDC	DC measurement
MMET	Meteorological conditions
MMXU	Measurements
STMP	Temperature measurements
WALM	Wind power plant alarm information
WAPC	Wind power plant active power control information
WCNV	Wind turbine converter information
WGEN	Wind turbine generator information
WNAC	Wind turbine nacelle information
WREP	Wind turbine report information
WROT	Wind turbine rotor information
WRPC	Wind power plant reactive power control information
WSLG	Wind turbine state log information
WTRF	Wind turbine transformer information
WTRM	Wind turbine transmission information
WTOW	Wind turbine tower information
WTUR	Wind turbine general information
WYAW	Wind turbine yawing information
XSWI	Circuit switch
ZINV	Inverter
ZRCT	Rectifier

APPENDIX B WIND POWER SCHEDULED OUTPUT DATA

Period	Day-ahead /MW	RTD /MW	Period	Day-ahead /MW	RTD MW
31	83.00	100.00	48	75.00	75.00
32	83.00	100.00	49	75.00	75.00
33	83.00	108.37	50	75.00	83.33
34	83.00	108.33	51	75.00	83.33
35	83.00	108.33	52	67.00	83.33
36	75.00	100.00	53	67.00	83.33
37	75.00	91.67	54	67.00	83.33
38	75.00	91.67	55	67.00	75.00
39	75.00	91.67	56	67.00	75.00
40	75.00	91.67	57	67.00	75.00
41	75.00	91.67	58	67.00	75.00
42	75.00	83.33	59	58.00	75.00
43	83.00	83.33	60	58.00	83.33
44	83.00	83.33	61	58.00	83.33

45	83.00	83.33	62	50.00	91.67
46	67.00	75.00	63	50.00	91.67
47	67.00	75.00	64	50.00	91.67
...	...	...	...	...	...
65	58.00	91.67	82	58.00	75.00
66	58.00	75.00	83	58.00	91.67
67	58.00	75.00	84	58.00	83.33
68	58.00	75.00	85	75.00	83.33
69	33.00	66.67	86	75.00	92.13
70	33.00	66.67	87	75.00	92.13
71	33.00	58.33	88	92.00	92.13
72	33.00	58.33	89	92.00	90.85
73	58.00	58.33	90	92.00	91.66
74	58.00	66.67	91	92.00	91.66
75	58.00	66.67	92	83.00	91.66
76	58.00	75.00	93	83.00	90.49
77	58.00	75.00	94	83.00	90.49
78	58.00	83.33	95	83.00	90.49
79	58.00	75.00	96	83.00	90.49
80	58.00	75.00			
81	58.00	75.00			

APPENDIX C CONVENTIONAL UNITS OUTPUT DATA

	Period	G1	G2	G3	G4	G5	G6	G7	G8	G9
DA	31	337.7	237.2	340.0	193.5	260.0	186.9	86.6	34.9	21.0
	32	337.7	237.2	340.0	193.5	260.0	186.9	86.6	34.9	21.0
	33	375.5	265.3	340.0	219.4	260.0	210.8	100.3	45.0	29.5
	34	375.5	265.3	340.0	219.4	260.0	210.8	100.3	45.0	29.5
	35	375.5	265.3	340.0	219.4	260.0	210.8	100.3	45.0	29.5
	36	377.5	266.8	340.0	220.8	260.0	212.1	101.1	45.6	30.1
	37	413.6	295.0	340.0	246.7	260.0	235.8	115.1	56.5	39.5
	38	413.6	295.0	340.0	246.7	260.0	235.8	115.1	56.5	39.5
	39	413.6	295.0	340.0	246.7	260.0	235.8	115.1	56.5	39.5
	40	413.6	295.0	340.0	246.7	260.0	235.8	115.1	56.5	39.5
	Period	G1	G2	G3	G4	G5	G6	G7	G8	G9
RTD	31	332.4	233.5	340.0	190.5	260.0	184.0	85.4	34.5	20.8
	32	332.4	233.5	340.0	190.5	260.0	184.0	85.4	34.5	20.8
	33	367.6	259.8	340.0	214.9	260.0	206.5	98.4	44.3	29.2
	34	367.6	259.8	340.0	214.9	260.0	206.5	98.4	44.3	29.2
	35	367.6	259.8	340.0	214.9	260.0	206.5	98.4	44.3	29.2
	36	369.6	261.4	340.0	216.4	260.0	207.8	99.2	44.9	29.7
	37	408.3	291.3	340.0	243.7	260.0	233.0	113.8	56.0	39.3
	38	408.3	291.3	340.0	243.7	260.0	233.0	113.8	56.0	39.3
	39	408.3	291.3	340.0	243.7	260.0	233.0	113.8	56.0	39.3
	40	408.3	291.3	340.0	243.7	260.0	233.0	113.8	56.0	39.3

V. CONCLUSIONS

To meet the demand of the further development of renewable energy, in this paper, a real-time generation dispatch applied for smart grid, to actively absorb renewable energy, reduce its influence of fluctuation and optimize the gird's operation cost, is proposed. Besides, the suitable communication architecture is presented. Using MATLAB, the proposed generation dispatch model was implemented to estimate the 10 unit test system with a wind farm. From the simulation results, the suitability and availability of the studied generation dispatch model can be proved well.

As a matter of fact, for the proposed real-time generation dispatch model's practical application, some key technical problems should be considered, such as the detailed construction of a real intelligent communication network with high-speed two-way functions. These tasks will be performed in future. It can be believed that, along with the further improvement of modern communication technology and real-time generation schedule, the application of renewable energy into the smart grid will get more attentions and supports.

APPENDIX A APPENDIX A

Description of logical node abbreviations used in renewable energies information model based on IEC 61850.

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