

Coordinated control of AGC with consideration PEVs and controllable loads in power system with renewable energy sources

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Abstract. According to the complementary nature of different power supplies, we proposed an optimal control system model based on model predictive control (MPC) in existing automatic generation control (AGC) framework to support effective operation of the AGC with the considerations of plug-in electric vehicles (PEVs) and controllable loads, to achieve full utilization of renewable energy sources, and to reduce the imbalance between supply and demand in the grid as far as possible. According to dynamics and update rate of power supplies at different time scales, as well as their actual power and energy constraints, MPC load distributor can find a solution of the MPC programming problem to well control the reserve capacities from the conventional generators, PEVs and controllable loads so that the tracking error of area control error (ACE) can be minimized. Massive simulation studies were performed under various control elements, such as different power combinations, different control reserve capacities, different ramp rates and different input control update rates. Simulation results are presented to demonstrate the effectiveness of the proposed method.

1. Introduction

Against the backdrop of the intensifying contradictions between economic development, energy supply and environment pollutions, energy conservation, emission reduction and reducing the dependence of fossil fuels have become an urgent problem to be solved for sustainable development.

In this backdrop, renewable energy sources (RESs) were followed with interest by the governments and power generation enterprises. The share of RES in electricity consumption [1-4]: 14% in Germany 2007 and 50% is expected in 2030; In Denmark, the RESs are planned to account 30% of total energy consumption in 2025. Therefore, the future grid will be a grid with high penetration of renewable energy sources. Considering characteristics of intermittent and random, the large-scale integration of RESs will bring significant influence to the operation of power system. The increase of wind power penetration will bring great challenges to the balance ability and load frequency control of system [5,6].

PEVs are kinds of excellent controllable loads and power resources, there will be a rapid growth of their number in the next 20 years. In Denmark, an estimated 10% cars will be PEVs in 2020; In China, by 2030, the peak charging load of PEVs will be 479GW which accounts for 54.8% of the total installed capacity in 2009 [7,8].

As a kind of flexible controllable load and power/energy storage unit, PEVs' aggregator has a



significant influence on both sides of the supply and demand for power system. PEVs can stabilize power fluctuations, reduce the adverse effects of RESs' intermittent, promote full utilization of RESs and provide ancillary services to the power system, such as frequency regulation, spinning reserve etc., they have an important impact on the reliable and economic operation of the future power system. Hence, the program EDISON which is on the study of PEVs integrated in grid intelligently and its complementary optimization with wind power was launched in Denmark recently [9,10]; technologies supported the development of PEVs are treated as major projects of the National High Technology Research and Development Program ("863"Program) of China [11]. A similar situation also occurred in other countries.

Because of the intermittent and random of RESs, the frequency and latitude of its output fluctuation are large and its balance resources need to be rapid response. The PEVs with millisecond quick response can provide ancillary services as electrical source and controllable loads on both sides of the supply and demand for power system.

In the smart grid, there is a kind of loads whose charging time is flexible named controllable loads, such as heating equipment, refrigeration equipment and storage equipment. It is a key concept of the smart grid and also a research method which is recently been highly regarded to control such loads for power balance. It's better for producing more regular and smoother power by combining the methods with the control strategies of renewable source generation and energy storage equipment [12].

A method which was regarded as a complement to existing AGC system was proposed in [12] by coordinating control the renewable energy, storage batteries, thermoelectric and controllable loads to support the load frequency control (LFC). In [13], the power adjustment on supply-side and the energy consumption of residential and commercial users on demand-side were joint controlled in order to reduce the imbalance between supply and demand sides of the grid. In [14], auxiliary services managers were used to dispatch the control reserve capacity of time-varying and conventional source for the sake of optimal aggregator of PEVs and grid frequency control.

An optimal control system model based on MPC was proposed in this paper. Based on the actual power and energy constraints of conventional generator units, PEVs and controllable loads, their control reserve capacity can be coordinated control to support the effective operation of AGC, to achieve full utilization of renewable energy sources and system power balance and to maintain system frequency stability. The performances of proposed control system which takes advantage of the complementary nature of different sources and MPC optimization control algorithm were simulated and different combinations of sources, different control update rate, different control reserve capacity and its change rate and other control factors were taken into account.

2. Control system

In the future power system, the grid will absorb large scale renewable energy and the existing generation dispatching mode will no longer be the most economic mode. Tracking the prediction curve of renewable energy through the demand dispatching mode is an effective complement to the future power system dispatching. Generation dispatching can balance the uncontrollable loads using controllable sources and demand dispatching balance the predicted power of renewable energy using controllable loads. Therefore, the off-plan unbalanced power in the future system can be expressed as:

$$\Delta P_t^{\text{sys}} = \Delta P_t^{\text{load}} - \Delta P_t^{\text{res}} \quad (1)$$

Where, ΔP_t^{sys} is system unbalanced power at t ; ΔP_t^{load} is the off-plan loads at t (Considering the PEVs load fluctuations and system normal load fluctuations); ΔP_t^{res} is the deviation of the predicted and actual power of renewable energy at t .

From (1), we can see that the integration of renewable sources will increase the fluctuation ΔP_t^{sys} . The existing AGC control attempts to match the average of generation and load over a time, the quality of tracking load changes is low [15]. Therefore, based on the existing AGC framework, the quick-response PEVs and controllable loads are incorporated into for the sake of providing control

reserve capacity. In order to take full advantage of renewable sources, they don't participate in primary and secondary frequency regulation and are not considered to provide frequency regulation reserve capacity, as figure 1 [16].

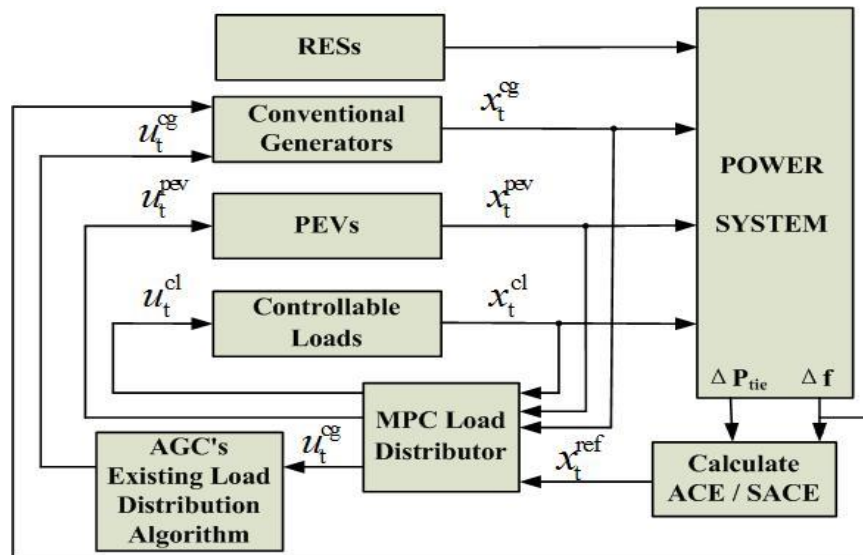


Figure 1. Block diagram of the control system model.

ACE of control areas was show as,

$$ACE_n = \Delta P_{tie} + K \Delta f \quad (2)$$

Where, ΔP_{tie} is the tie-line power deviation of control areas; Δf is the system frequency deviation; K is frequency deviation coefficient of control areas.

MPC load distributor whose function is to distribute smoothed ACE (SACE) to generator units, PEVs and controllable loads based on MPC algorithm is increased in existing AGC function diagram. The power to conventional generator units is distributed by regulation and economic allocation algorithms in the existing AGC. PEVs and controllable loads were managed and controlled by their aggregators. As an intelligent control system, aggregators are in charge of the aggregation of PEVs and controllable loads and control the output power of PEVs and controllable loads according to the power regulation of MPC load distributor [17-21].

The aggregator of PEVs eliminates the limits of the storage energy and charging requirements. PEVs aggregator can choose sufficient PEVs to provide the regulation power and their storage energy can satisfy the energy requirements of AGC [21].

Controllable loads can be conveniently controlled by simplifying their power change characteristics. Therefore, they are only considered as the interruptible loads in this paper.

Piecewise affine (PWA) model is the simplest extension of linear system model and is able to approximate the nonlinear system with arbitrary precision [22,23].

Based on above considerations, the PWA model of nonlinear time-varying system is shown as figure 1 [14,23,24],

$$\begin{aligned}
x_{t+1}^{pev} &= f_{PWA}^{pev}(x_t^{pev}, u_t^{pev}) \\
x_{t+1}^{cg} &= f_{PWA}^{cg}(x_t^{cg}, u_t^{cg}) \\
x_{t+1}^{cl} &= f_{PWA}^{cl}(x_t^{cl}, u_t^{cl}) \\
y_t &= x_t^{pev} + x_t^{cg} + x_t^{cl} - x_t^{ref} \\
(u_t^{pev}, u_t^{cg}, u_t^{cl}) &= f_{AD}(x_t^{pev}, x_t^{cg}, x_t^{cl}, x_t^{ref})
\end{aligned} \tag{3}$$

Where, x_t is the output power at t ; x_t^{ref} is SACE at t ; u_t is the output change rate at t ; y_t is the tracking error at t ; f_{PWA} is PWM function; f_{AD} is the status feedback control function based on the MPC load distributor.

3. Constraints of system

The qualitative descriptions of the system constraints were defined in this section. The research objective is the dynamic coordinating control of conventional generator units, PEVs and controllable loads, therefore, the main constraints contain their control reserve capacity, control input change rate and control update rate.

- Constrains of conventional generator units

1. P_{Max}^{cg} : Maximum output power of conventional generator units, hard constraint;
2. P_{Min}^{cg} : Minimum output power of conventional generator units, hard constraint;
3. u_{ramp}^{cg} : The limit of conventional generator units' ramp rate, hard constraint;
4. x_{Max}^{cg} : Maximum reserve capacity of conventional generator units, hard constraint;
5. x_{Min}^{cg} : Minimum reserve capacity of conventional generator units, hard constraint;
6. T_{cg} : AGC cycle of conventional generator units, soft constraint.

- constraints of PEVs

1. u_{ramp}^{pev} : The limit of PEVs' output change rate, hard constraint;
2. x_{Max}^{pev} : Maximum reserve capacity of PEVs, hard constraint;
3. x_{Min}^{pev} : Minimum reserve capacity of PEVs, hard constraint;
4. T_{pev} : AGC cycle of PEVs, soft constraint.

- Constraints of controllable loads

1. u_{ramp}^{cl} : The limit of controllable loads' output change rate, hard constraint;
2. x_{Max}^{cl} : Maximum reserve capacity of controllable loads, hard constraint;
3. x_{Min}^{cl} : Minimum reserve capacity of controllable loads, hard constraint
4. T_{cl} : AGC cycle of PEVs, soft constraint.

4. System models with constraints

Conventional generator units can be abstracted as first-order processes and PEVs and controllable loads also can be abstracted as first-order processes under the control of their aggregators [12,15,19,24-26]. Therefore, under the control of MPC load distributor, the control inputs of conventional generator units, PEVs and controllable loads, are equal to their output increments, i.e. the steady-state output power is equal to the given regulation power.

$$\begin{aligned}
x_{t+1}^{pev} &= x_t^{pev} + u_t^{pev} \\
x_{t+1}^{cg} &= x_t^{cg} + u_t^{cg} \\
x_{t+1}^{cl} &= x_t^{cl} + u_t^{cl}
\end{aligned} \tag{4}$$

The control update rate should be appropriate to assume the stability and favorable performance of AGC system. Conventional generator, PEVs and controllable loads needs to respond the switch of control signal and regulate the control variables in order under the constraints of control update rate. The PWA function of them is shown as:

$$f_{PWA}(x_t, u_t) = \begin{cases} x_t + u_t & t \bmod T = 0 \\ x_t & t \bmod T \neq 0 \end{cases} \tag{5}$$

The state equation (4) can be rewritten as equation (6) in the help of the constraints' parameters above and equation (5).

$$\begin{aligned}
x_{t+1}^{pev} &= \begin{cases} x_t^{pev} + u_t^{pev} & t \bmod T_{pev} = 0 \\ x_t^{pev} & t \bmod T_{pev} \neq 0 \end{cases} \\
x_{t+1}^{cg} &= \begin{cases} x_t^{cg} + u_t^{cg} & t \bmod T_{cg} = 0 \\ x_t^{cg} & t \bmod T_{cg} \neq 0 \end{cases} \\
x_{t+1}^{cl} &= \begin{cases} x_t^{cl} + u_t^{cl} & t \bmod T_{cl} = 0 \\ x_t^{cl} & t \bmod T_{cl} \neq 0 \end{cases}
\end{aligned} \tag{6}$$

The constraints of equation (6) are shown as the in equation (7).

$$\begin{aligned}
x_{Min}^{pev} &\leq x_t^{pev} \leq x_{Max}^{pev} \\
x_{Min}^{cg} &\leq x_t^{cg} \leq x_{Max}^{cg} \\
x_{Min}^{cl} &\leq x_t^{cl} \leq x_{Max}^{cl} \\
|u_t^{pev}| &\leq u_{ramp}^{pev} \\
|u_t^{cg}| &\leq u_{ramp}^{cg} \\
|u_t^{cl}| &\leq u_{ramp}^{cl}
\end{aligned} \tag{7}$$

T_{cg} is commonly 2-4s in the existing AGC. In order to avoid unnecessary PEVs battery charging and discharging frequently and accelerating deterioration of the battery, T_{pev} is greater than T_{cg} ; And for the same reason, T_{cl} is greater than T_{cg} , for the sake of avoiding unnecessary wear and tear of controllable loads related equipment. Through the switch function, control inputs of PEVs and controllable loads u_t^{pev} and u_t^{cl} are less than that of conventional generator units, thus it approximates to the actual system.

5. Load distributor based on MPC

5.1. MPC principle

MPC is a widely accepted control method which combined with the characteristics of optimization and predictive control. According to the system state $x(k)$ of a given model, MPC can do the iterative solution for Constrained Finite-time Optimal Control (CFTOC) problems in the limited predicted time

domain $[k, k+N \cdot k]$ at each sampling step k . In each iteration, only the first step control output $u(k)$ was realized, thus such optimization could be repeated in a new system state $x(k+1)$. Unlike well-known programs provided by auxiliary service, MPC could provide different time scales optimal predicted control.

5.2. MPC load distributor

MPC has good control effects, strong robustness and it can overcome the uncertainty and nonlinear of processes. Therefore, the control of the model and first-order processes abstracted of equations (2) and (3) can be solved by MPC.

MPC can realize the self-optimization and object tracking of steady-state object by solving the Linear Program (LP) problem and Quadratic Program (QP) problem. MPC is a good choice for the problem with given control reserve capacity and grid frequency regulation.

MPC load distributor can conveniently provide different time scale dynamic state and frequency and dispatch the control reserve capacity from conventional and time-varying sources.

Based on above consideration, a MPC optimal predicted control scheme based on multiple control update rate which plays a role of a framework coordinating time-varying and conventional generator units, realizes better system optimal control performance and reduces imbalance of supply and demand was proposed [18,27-29].

For the given limited predicted time domain N and at each step t , MPC load distributor solves the following planning problem:

$$\text{Min } J = \begin{cases} \sum_{i=0}^N R \|x_i'^{pev} + x_i'^{cg} + x_i'^{cl} - x_i'^{ref}\|_1 + \\ \sum_{i=0}^{N-1} Q_i^1 \|x_i'^{pev}\|_1 + Q_i^2 \|x_i'^{cg}\|_1 + Q_i^3 \|x_i'^{cl}\|_1 \end{cases} \quad (8)$$

Equation (8) needs satisfy the constrains of equations (9) and (10).

$$\begin{aligned} x_{i+1}'^{pev} &= f_{PWA}^{pev}(x_i'^{pev}, u_i'^{pev}) \\ x_{i+1}'^{cg} &= f_{PWA}^{cg}(x_i'^{cg}, u_i'^{cg}) \\ x_{i+1}'^{cl} &= f_{PWA}^{cl}(x_i'^{cl}, u_i'^{cl}) \\ x_0'^{ref} &= x_t'^{ref} \quad x_0'^{pev} = x_t'^{pev} \\ x_0'^{cg} &= x_t'^{cg} \quad x_0'^{cl} = x_t'^{cl} \end{aligned} \quad (9)$$

$$\begin{aligned} x_{Min}^{pev} &\leq x_i'^{pev} \leq x_{Max}^{pev} \\ x_{Min}^{cg} &\leq x_i'^{cg} \leq x_{Max}^{cg} \\ x_{Min}^{cl} &\leq x_i'^{cl} \leq x_{Max}^{cl} \\ |u_i'^{pev}| &\leq u_{ramp}^{pev} \\ |u_i'^{cg}| &\leq u_{ramp}^{cg} \\ |u_i'^{cl}| &\leq u_{ramp}^{cl} \end{aligned} \quad (10)$$

In equations (7)-(9), x'^{pev} , x'^{cg} , x'^{cl} , u'^{pev} , u'^{cg} , u'^{cl} are variable; $x_t'^{ref}$, $x_t'^{pev}$, $x_t'^{cg}$, $x_t'^{cl}$ are the initial state at step t .

In the objective function of optimization problem, the first summation term is to punish the tracking error, weight of penalty cost is R ; the second summation term is to obtain the state cost of

conventional generator units, PEVs and controllable loads, Q_i^1 , Q_i^2 , Q_i^3 are the cost weight of state variable.

Objective function is expressed by 1-norm in order to solve it conveniently using TOMLAB/CPLEX.

6. Simulations

6.1. Simulation model and parameters

Renewable energy is wind power in the system and models of wind power and load stems from [30]. Per-unit values of load output is $P_{Max}^{load}=11$, $P_{Min}^{load}=8$; Per-unit values of wind turbine output is $P_{Max}^{res}=5$, $P_{Min}^{res}=1.5$. inertial constant of equivalent unit is $M_{eq}=10s$, damp constant is $D=1.6$, $R_{eq}=5\%$. Per-unit values of equivalent unit output is $P_N^{cg}=6$, $P_{Max}^{cg}=6.8$, $P_{Min}^{cg}=5.2$. Penetration of wind power is 36%.

6.2. Simulation cases and results

There are 5 simulation cases and the parameters in table 1. The output and frequency deviation that only equivalent unit participates in control were studies in cases 1. The output and frequency deviation that PEVs and generator unit with the same control reserve capacity and control input change rate and the different control update rate participate in control were respectively studies in cases 2 and case 3. The impacts on system output and frequency deviation of whole system coordinated control were studied in case 4 and case 5. In case 4, control reserve capacity and control input change rate were calculated when the performance achieve that of case 3 with generator unit, PEVs and controllable loads participating in coordinated control; case 5 is based on case 4 and increases the control reserve capacity and control input change rate.

Table 1. Simulation example parameters.

| cases | group | generator unit | generator unit | PEVs | PEVs | PEVs | controllable loads | controllable loads | controllable loads |
|-------|-------------|--------------------|----------------|--------------|---------------------|-------------|--------------------|--------------------|--------------------|
| | x^{cg}/pu | u_{ramp}^{cg}/pu | T_{cg}/s | x^{pev}/pu | u_{ramp}^{pev}/pu | T_{pev}/s | x^{cl}/pu | u_{ramp}^{cl}/pu | T_{cg}/s |
| 1 | (-0.8)-0.8 | 0.05 | 4 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | (-0.8)-0.8 | 0.05 | 4 | (-2)-2 | 1 | 16 | 0 | 0 | 0 |
| 3 | (-0.8)-0.8 | 0.05 | 4 | (-2)-2 | 1 | 8 | 0 | 0 | 0 |
| 4 | (-0.8)-0.8 | 0.05 | 4 | (-1)-1 | 0.5 | 8 | (-1)-1 | 0.5 | 16 |
| 5 | (-0.8)-0.8 | 0.05 | 4 | (-2)-2 | 1 | 8 | (-2)-2 | 1 | 16 |

All the simulations were realized on Matlab7.1 and MPC optimization problems were solved by TOMLAB/CPLEX. x_t^{ref} is in a range of $[-2.41, 3.52]$, the initial value of generator unit is $P_0^{cg}=6$.

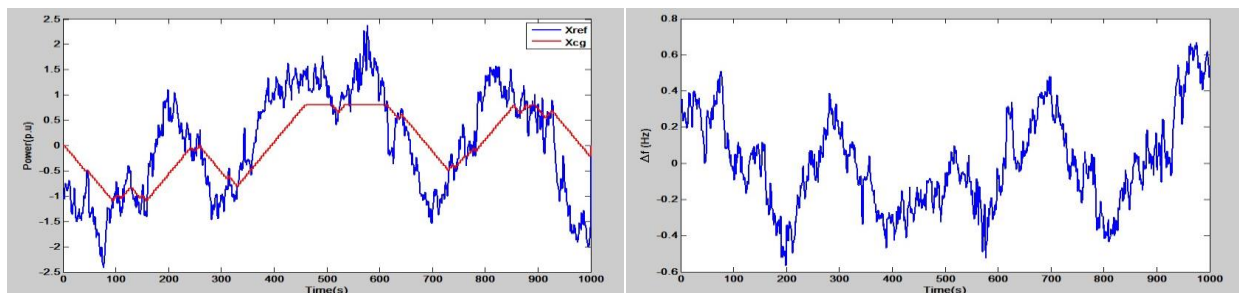


Figure 2. The output and frequency deviation of control of only generators in example 1.

According to the GB/T15945-1995, the grid frequency should be in the range of $50 \pm 0.2\text{Hz}$ in 98% of time.

The output and frequency deviation of case 1 are shown in figure 2. There are 457 data exceeding the permissive frequency deviation $\pm 0.2\text{Hz}$, the maximum frequency minus deviation is -0.566 and the maximum frequency positive deviation 0.669. Obviously, the range of frequency deviation is large and there are large amount of unqualified data in case 1.

Comparing the figures 3 and 4, the output power of PEVs is smoother but the frequency fluctuation is large in case 2. There are 111 data exceeding the permissive frequency deviation, the maximum frequency minus deviation is -0.392 and the maximum frequency positive deviation 0.597 in case 2. And there are 39 data exceeding the permissive frequency deviation, the maximum frequency minus deviation is -0.257 and the maximum frequency positive deviation 0.381 in case 3. With the same control reserve capacity and control input change rate, it is observed that the data exceeding the permissive frequency deviation reduce by half and the range of frequency deviation narrows significantly with the generator units and PEVs of small control update rate.

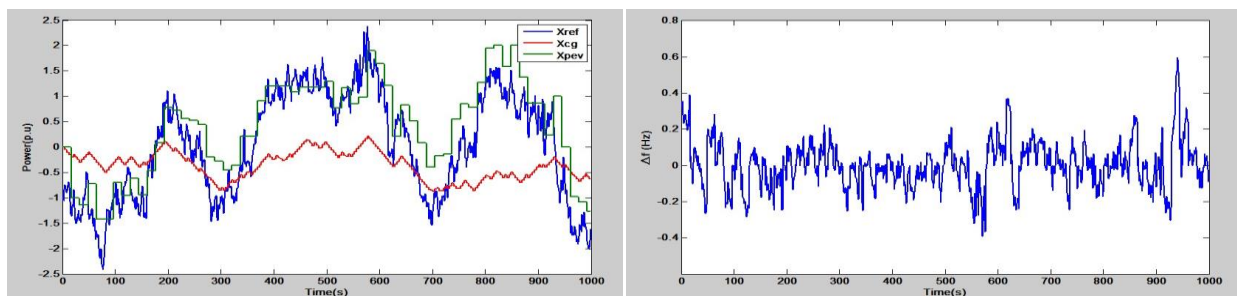


Figure 3. The output and frequency deviation of coordinated control of PEVs and generators in example 2.

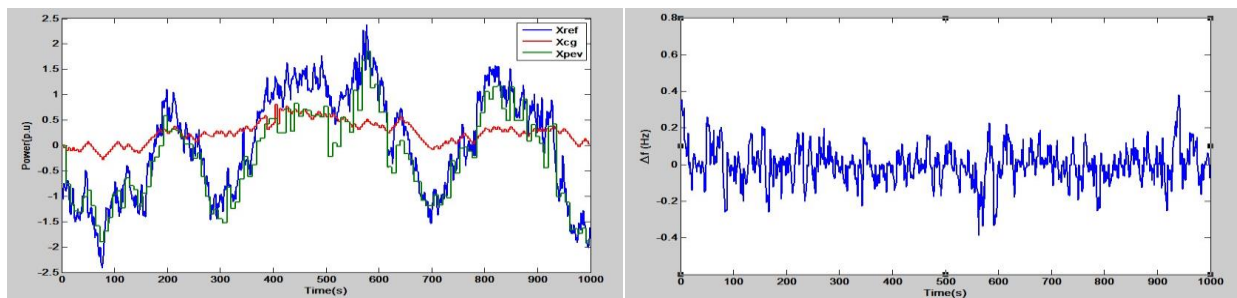


Figure 4. The output and frequency deviation of coordinated control of PEVs and generators in example 3.

Figures 5 and 6 show the impact on frequency deviation when the control reserve capacity and control input change rate are doubled with the same control update rate of generator units, PEVs and controllable loads. There are 40 data exceeding the permissive frequency deviation, the maximum frequency minus deviation is -0.386 and the maximum frequency positive deviation 0.379 in case 4. There are 21 data exceeding the permissive frequency deviation, the maximum frequency minus deviation is -0.256 and the maximum frequency positive deviation 0.295 in case 5. With conventional generator, PEVs and controllable loads coordinate control, the larger the control reserve capacity and control input change rate are, the smaller the range of frequency deviation. The data exceeding permissive frequency reduce by 47.5%.

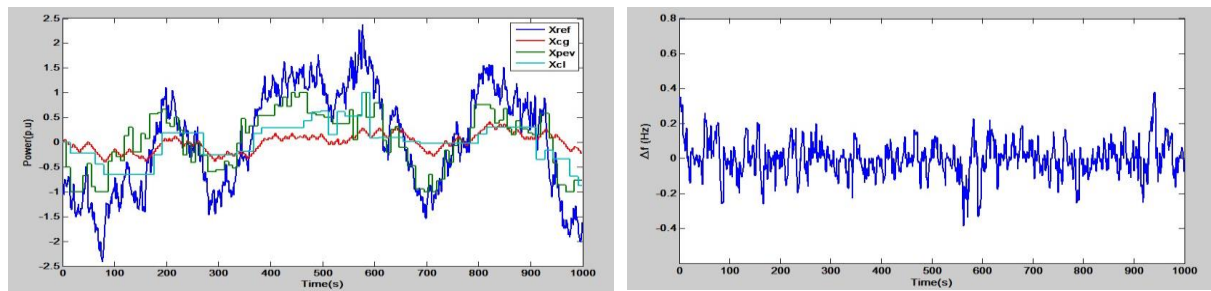


Figure 5. The output and frequency deviation of coordinated control of controllable loads, PEVs and generators in example 4.

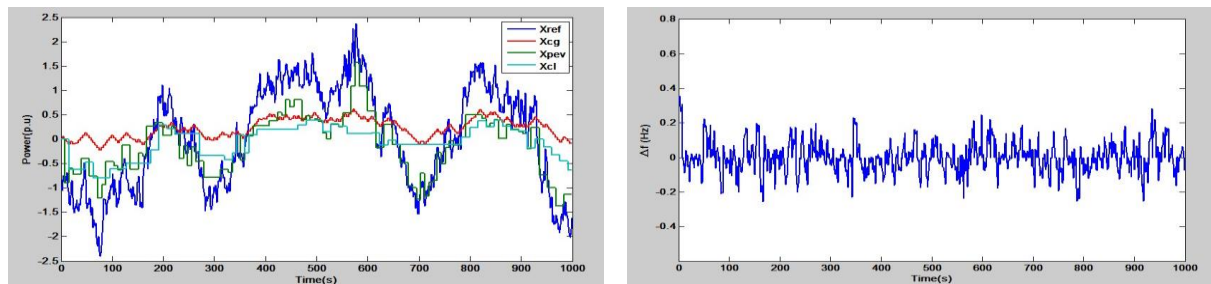


Figure 6. The output and frequency deviation of coordinated control of controllable loads, PEVs and generators in example 5.

The frequency pass rate and RMS of frequency deviation of the 5 cases are shown in table 2.

Table 2. Frequency pass rate and RMS of all examples.

| Cases | Frequency pass rate (%) | Frequency RMS (Hz) |
|-------|-------------------------|--------------------|
| 1 | 54.3 | 0.260 |
| 2 | 88.9 | 0.148 |
| 3 | 96.1 | 0.109 |
| 4 | 96.0 | 0.121 |
| 5 | 97.9 | 0.110 |

Because there isn't control for the wind power models in simulation system but the impact of output power due to sudden change random fluctuations can be reduced by control in the actual wind power system [12], the frequency pass rate of case 5 will be higher and satisfy the requirement of GB/T15945-1995.

Table 2 shows that the frequency pass rate is much lower acceptance criterion and the effects are poor comparing with other cases. It demonstrates that only the generation control cannot satisfy the requirement of frequency control, unless the penetration of wind power is cut down and the grid integrated wind power is reduced.

Comparing with case 1, frequency pass rate is higher and higher and RMS of frequency deviation is obviously reduced along with the coordinate control of different control elements in system. Coordinate control based on MPC can adopt high penetration of wind power, make better use of wind power, reduce the frequency fluctuation and improve the power quality.

According to frequency pass rate, the pass rate with all the elements is higher than that with parts of elements. According to RMS of frequency deviation, although case 3 and case 4 have the same control reserve capacity, the effect of case 3 is better while control input change rate is faster and input control update rate is smaller in case 3. However, the adjustment is limited because of the control object constraints to the control input change rate and update rate. Case 5 illustrates that the coordinate

control with all the elements can improve control reserve capacity in the case of the same control input change rate of case 3 and the same control update rate of case 4. Meanwhile, it can both satisfy the requirements of frequency pass rate and implement a good control effect.

7. Conclusions

The proposed model of control system based on MPC load distributors realized the optimal coordinate control of generator units, PEVs and controllable loads. The simulation results show that the proposed control system can take full advantage of renewable sources, keep the power balance and support the operation of AGC; the control elements of different combination of electrical source, different control update rate, different control reserve capacity and its change rate can significantly reduce the fluctuation of system output; the impacts on system frequency deviation of each control elements are different, but the coordinate control of all the elements and higher control reserve capacity can satisfy requirements of both the frequency pass rate and the frequency control effects; However, the larger control update rate can't completely control the sudden change random fluctuation even with the full system control.

An appropriate control frame for optimal control capacity and its combination and the application of coordinate control based on MPC are the subjects for future research.

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