Cyber-physical Power System Modeling for Timing-driven Control of Active Distribution Network

Yun Wang, Dong Liu, Xiaochun Xu, and Hui Dai

***Abstract*—In a cyber-physical power system, active distribution network (ADN) facilitates the energy control through hierarchical and distributed control system (HDCS). Various researches have dedicated to develop the control strategies of primary devices of ADN. However, an ADN demonstration project shows that the information transmission of HDCS may cause time delay and response lag, and little model can describe both the ADN primary device and HDCS as a cyber-physical system (CPS). In this paper, a hybrid system based CPS model is proposed to describe ADN primary devices, control information flow, and HDCS. Using the CPS model, the energy process of primary devices and the information process of HDCS are optimized by model predictive control (MPC) methodology to seamlessly integrate the energy flow and the information flow. The case study demonstrates that the proposed CPS model can accurately reflect main features of HDCS, and the control technique can effectively achieve the operation targets on primary devices despite the fact that HDCS brings adverse effects to control process.**

***Index Terms*—Active distribution network (ADN), cyber-physical system (CPS), hybrid system, hierarchical and distributed control system.**

I. INTRODUCTION

WITH the rapid development of information technology, how to properly integrate the information system with the traditional industrial control system has become a major research challenge in various application domains. This spawns the new concept of cyber-physical system (CPS), aiming at handling the close interaction between the information system and real physical system [1], [2]. In the real-world application, especially in the industrial production, the control system needs to be tightly combined with the controlled object.

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A smart grid possesses all the essential characteristics of a CPS [3], [4]. In terms of concepts, a roadmap is given in [5], and the frame and annotation of smart grid CPS are presented in [6], [7]. In terms of modeling and control, the directed graph is used in [8] to model hierarchical control systems and evaluate the impacts of information system events on power grid control. In [9], communication delay is considered in developing the dynamic model and control process of primary system to sustain voltage stability. According to the real time physical system, a modeling and control method is built in [10] for CPS to reduce instantaneous power consumption.

As an advanced form of smart grid, active distribution network (ADN) [11] explores hierarchical and distributed control system (HDCS) to realize control function [12], and it has basic features of CPS. Distribution generation control [13] and voltage control [14] have been tested in an ADN demonstration project.

However, the existing control method and model are idealized, and only consider the primary system of ADN. The typical design of HDCS consists of three levels of controllers and stretches across several power supply areas. Thus, the time delay is a key problem which may affect control effect. In the debugging stage of an ADN demonstration project in Guangdong province, China, the time delay leads to severe response lag of distributed generators (DGs). Although the control results have been promoted in the demonstration project by adjusting proportional-integral (PI) parameters, the essential principal is still unknown.

There are two reasons for the problems above: ① the controlled objective mainly focuses on the energy flow (physical system), while the HDCS and the control information flow are not considered; ② the existing control model and strategy mainly focus on continuous dynamic process (physical process), while the discrete state switching (information process) is not included.

Just like the adverse phenomenon in the demonstration project, time delay is difficult to be avoided even if the communication infrastructure and the performance of controllers are all improved. The most feasible way is to consider the time delay in the control input, and build a control model integrating with CPSs.

This paper aims to design such an integration model which considers time delay caused by HDCS. Each control input computed by this model will include relevant attribution of time delay, thus the adverse influence can be reduced as much as possible. Firstly, the HDCS of ADN and the information flow are analyzed, and the impact of HDCS on primary system is studied. Then, taking the control of ADN flexible load as an example, a hybrid system based CPS model is built which integrates the primary device, the control information flow, and the HDCS structure. According to the integration model, a model predictive control (MPC) strategy is designed to optimize the load operation. Finally, the model and strategy are verified with extensive simulations.

II. HDCS and Information Flow of ADN

A. Information Flow of ADN

The HDCS completes all the measurement, data transmission, computation and control in ADN, and it is the most important tool to realize ADN function. The control system of ADN is shown in Fig. 1. It depicts the structure of HDCS including global energy management system (GEMS), area coordination controller (ACC), and source network coordination controller (SNCC) [12], where ESS stands for energy storage system and PV stands for photovoltaic.

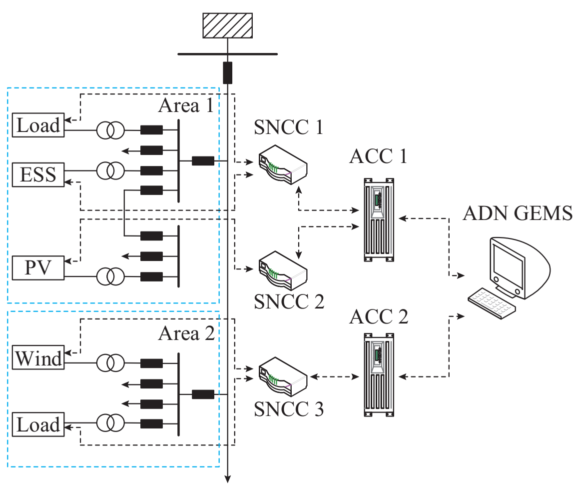

Fig. 1. Control system of ADN.

In HDCS, the controlled primary devices are connected to different SNCCs according to the category or performance of devices. SNCCs of each control area receive and execute the control commands from ACC. All SNCCs and ACCs are managed and coordinated by GEMS.

The controllers of HDCS exchange information with each other through communication network. Taking the control of ADN flexible load under power shortage condition as an example [13], the information flows in the control process are listed in Table I, which shows that the information flows cover all the control layers of HDCS and ADN, and that the controllers complete the missions such as target computation, target allocation, and information transmission.

As shown in Fig. 2, the optimal target of flexible load is computed by GEMS and is sent to ACC according to the control area of load. Then, the corresponding control target is allocated to SNCC which manages the load operation.

The control information of HDCS depends on diverse control function. It could induce different information processing modes, which leads to different device control effects. These need to be considered in the control target computation.

TABLE I
Information Flows of MPC for ADN Flexible Load

Layer	Information flow	Start	End
Global layer	Measurement information of main nodes	SNCC	GEMS
	System predictive information; flexible load control target	GEMS	ACC
Area layer	Area optimal target	GEMS	ACC
	Device control target in area	ACC	SNCC
Device layer	Device control target	ACC	SNCC
	Device operation information	SNCC	GEMS

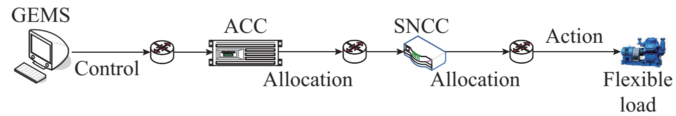

Fig. 2. Control information route of MPC for ADN flexible load.

B. Integration of ADN Primary System and HDCS

As mentioned above, the control target of ADN primary system can eventually be achieved by changing the control parameters. However, it is not clear how the control information affects the primary process . Thus, in order to achieve a more effective control, the working process of HDCS needs to be carefully studied and significantly improved.

Different from the primary system, the dynamic characteristic and the spatio-temporal feature of control system are unable to be completely represented by differential-algebraic equations which need to be replaced by logical description. Therefore, as shown in Fig. 3, the impacts of HDCS on ADN primary system include four aspects.

1) Aspect 1: transition logic of information flow. It describes the transition rules of control information by logical form which reflects information process structure of different control functions. Similar to the two structures in Fig. 3, there are two channel choices for the information from GEMS to ACC in Fig. 3(b), while only one in Fig. 3(a).

2) Aspect 2: structure of action objects. Even if the same control functions act on the same controlled objects, the computation and action of control information are determined by the structure of objects. In Fig. 3, although the control information is finally acted on N devices, the device group in Fig. 3(a) is controlled synchronously after the control information traverses each node of HDCS. However, in Fig. 3(b), the information of every controlled device is computed and sent respectively, and the devices are controlled asynchronously.

3) Aspect 3: information transition time. There is time consumption in the processing and communication procedure of controllers. Figure 3 indicates the information procedure of HDCS by time interval Δt. In addition, the total time consumption is related to information flow transition logic.

4) Aspect 4: information processing capacity. When controllers and communication devices process the control infor-

mation, it is impossible to execute unlimited threads, thus the limited processing capacity leads to stagnation. If the ACC in Fig. 3 can only process one control signal at a time, the subsequent information should stay in the GEMS or node 2.

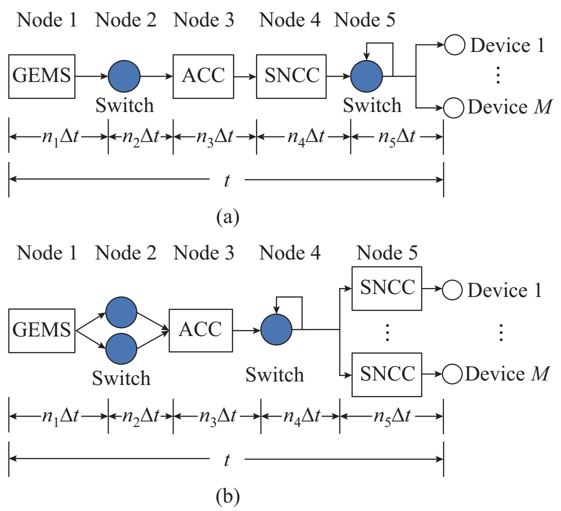

Fig. 3. Influence factor of information flow for ADN control. (a) HDCS of chain structure. (b) HDCS structure with branch.

Four aspects reflect the main features of HDCS and its impact on control effect. That is, aspects 1 and 2 are associated with the spatial factor; aspect 3 is about time effect; and aspect 4 is the attribute of HDCS itself.

In order to combine these four aspects of impacts with the ADN primary system, a logic based constraint model can be used to represent the impact and merged into the primary control model. Subsequently, the impacts of HDCS can be considered in the control problem.

III. Hybrid System Based ADN Modeling and Control

A. ADN Integration Model Considering Information Flow

In this subsection, the control of ADN flexible load is used as an example to illustrate the CPS model which integrates energy and control information flow.

1) Hybrid System Based Primary Device Model

The hybrid system gives the integration of information and physical process, which is an ideal tool to describe continuous and discrete characteristics of the system. Some literatures define the physical laws of controlled object including continuous dynamic and event-driven state as hybrid system [15]. In [16] and [17], the mixed logical dynamic (MLD) [18] based modeling method and the control strategies are studied. Moreover, properties of communication, control, and information flow have also been modeled by logical or discrete form which can be brought into the hybrid system model of controlled object [19]. For example, in order to optimize the information route and the control effect, [20] studies the logical and sequential models for multi-hop wireless network based control system, which provides a foundation of this work.

The recursive equation (1) is the MLD model transformed from the traditional control model about control input $\boldsymbol{u}(t)$ by setting logical variable $\boldsymbol{\delta}(t)$. This equation reflects the dynamics of controlled device, and depicts the relationship of function output and control state switching in the control of ADN flexible load.

$$\boldsymbol{x}(t+\Delta t)=\boldsymbol{A}\boldsymbol{x}(t)+\boldsymbol{B}\boldsymbol{\delta}(t) \tag{1}$$

where $\boldsymbol{x}(t)$ is the state variable matrix; and $\boldsymbol{A}$ and $\boldsymbol{B}$ are the parameter matrices.

Unlike the time step Δt in [16], the Δt of (1) is determined according to the working performance of HDCS, because the information process is included and its time consumption is usually equals to the time step of primary device.

If there are j control states in (1), the logical variable vector $\boldsymbol{\delta}(t)=[\delta_1(t),\delta_2(t),\ldots,\delta_m(t),\ldots,\delta_j(t)]^{\mathrm{T}}$ needs to meet the equality constraint of (2) to ensure that there is only one control mode at a time.

$$\sum_{i=1}^{j}\delta_i(t)=1 \tag{2}$$

After flexible load is controlled by $\boldsymbol{\delta}(t)$ at time t, the logical variable vector switches to $\boldsymbol{\delta}(t+\Delta t)$. The switching follows a certain state transition principle which is made according to the finite state machine (FSM) of controlled device. For flexible load, there are always j equivalent states for choosing at any time.

2) Control Information Model

In order to model and control the information processing, it is necessary to set the number of control information of a primary device in a control period. The reason is that even through the same processing steps, the time consumption of different control information may not be the same due to the processing capacity and the stagnation time of HDCS. Therefore, when the effect of HDCS is taken into account, the primary device will not receive and execute control information by a fixed time interval in a control period but by a fixed number.

Figure 4 shows a comparison of control information. The scenario is that the primary device receives and executes 2 control signals in a control period of $T=20\Delta t$. If the information flow is not added, the control information will be executed at $t=10\Delta t$ and $t=20\Delta t$. When information flow is considered, the first signal U1 starts at $t=0$ and acts at $t=11\Delta t$; while the second signal U2 starts at $t=4\Delta t$ and arrives the device at $t=13\Delta t$, and it does not act until $t=19\Delta t$.

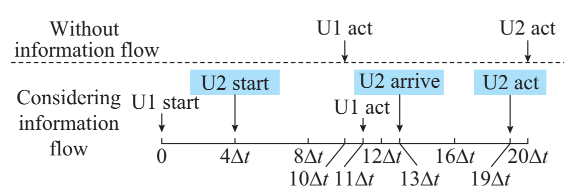

Fig. 4. Comparison of control information.

From Fig. 4, it also can be found that even if the control information has arrived at the primary device, the information may not be executed at once. This condition will be modeled by constraints later in this paper. Define the acting time of control information as the switching time, then the switching time from U1 to U2 is $t=19\Delta t$, and the acting control information from $t=12\Delta t$ to $t=19\Delta t$ is maintained at U1. Define $\boldsymbol{L}_{\text{sig}}(t)$ as a state target set for control information switching of time t, which represents the possible states of $t+\Delta t$. $\boldsymbol{L}_{\text{sig}}(t)$ usually includes two situations: one is that the control information of time $t+\Delta t$ keeps the same with time t; the other is that the control information switches to the next one.

$$\begin{cases} \boldsymbol{s}(t)=\boldsymbol{1}\rightarrow \bigcup\limits_{\boldsymbol{s}(t+\Delta t)\in \boldsymbol{L}_{\text{sig}}(t+\Delta t)} \boldsymbol{s}(t+\Delta t)=\boldsymbol{1} \\ \boldsymbol{s}(t)=[s_1(t) \quad s_2(t) \quad \dots \quad s_m(t) \quad \dots \quad s_s(t)]^{\text{T}} \end{cases} \tag{3}$$

Equation (3) models the transition of control information. $\boldsymbol{s}(t)$ is the control information vector of time t, which contains states of s control information in a control period. The element $s_m(t)\in\{0,1\}$, and when the m^{th} control information is executed by the primary device, only $s_m(t)=1$. According to the logical transition relationship of MLD [28], (3) can be transformed to the inequality of (4).

$$\boldsymbol{s}(t)\leq \sum_{\boldsymbol{s}(t+\Delta t)\in \boldsymbol{L}_{\text{sig}}(t+\Delta t)} \boldsymbol{s}(t+\Delta t) \tag{4}$$

Since the primary device can only execute one group of control information at a time, (5) can be obtained.

$$\sum_{m=1}^{s} s_m(t)=1 \tag{5}$$

Besides, the control information state $s_m(t)$ determines the logical variable $\boldsymbol{\delta}(t)$ at which time can be executed. Thus, the $\boldsymbol{\delta}(t)$ in (1) should be written as the sum of $s_m(t)\boldsymbol{\delta}(t)$.

3) HDCS Model

In HDCS, the location of control information $s_m(t)$ at time $t+\Delta t$ is determined by its location of time t and the processing capability of controller. Define $\boldsymbol{L}_{\text{con}}(t)$ as a state target set for the switching target of controller at time t. At time t, the control information $s_m(t)$ is processed in controller n, and it may be transferred to controller $n+1$ or stay at the controller n at time $t+\Delta t$. The switching targets of controllers n and $n+1$ are 2 elements of $\boldsymbol{L}_{\text{con}}(t)$.

$$\begin{cases} \boldsymbol{c}(t)=\boldsymbol{1}\rightarrow \bigcup\limits_{\boldsymbol{c}(t+\Delta t)\in \boldsymbol{L}_{\text{con}}(t+\Delta t)} \boldsymbol{c}(t+\Delta t)=\boldsymbol{1} \\ \boldsymbol{c}(t)=[\boldsymbol{c}_1(t) \quad \boldsymbol{c}_2(t) \quad \dots \quad \boldsymbol{c}_n(t) \quad \dots \quad \boldsymbol{c}_c(t)]^{\text{T}} \\ \boldsymbol{c}_n(t)=[c_{n1}(t) \quad c_{n2}(t) \quad \dots \quad c_{nm}(t) \quad \dots \quad c_{ns}(t)]^{\text{T}} \end{cases} \tag{6}$$

Equation (6) models the processing logic of HDCS. $\boldsymbol{c}(t)$ is a vector which consists of states of c HDCS nodes at time t. Its element $\boldsymbol{c}_n(t)$ is a s-dimension vector which describes the state of each control information at the n^{th} control node, and $c_{nm}(t)\in\{0,1\}$. Only when the m^{th} control information is processed at controller n, $c_{nm}(t)=1$. Like (3), (6) can be transformed to an inequality like (7).

$$\boldsymbol{c}(t)\leq \sum_{\boldsymbol{c}(t+\Delta t)\in \boldsymbol{L}_{\text{con}}(t+\Delta t)} \boldsymbol{c}(t+\Delta t) \tag{7}$$

Considering the processing capacity of every control node, if the controller n (except the GEMS and the actor) can process no more than w control information at the same time, (8) can be obtained.

$$\sum_{m=1}^{s} c_{nm}(t)\leq w \tag{8}$$

Moreover, the logical relationship between control information and HDCS should be described as (9), which means that: ① when the m^{th} information is acting on the primary device, this information must arrive at the actor c, or the proposition of (9) is false; ② when the m^{th} information is not executed, it may arrive at actor c.

$$s_m(t)=1\rightarrow c_{cm}(t)=1 \tag{9}$$

Equation (9) can also be transformed to (10).

$$s_m(t)\leq c_{cm}(t) \tag{10}$$

B. MPC of ADN Considering Information Flow

Based on (1) to (10), MPC can be used to optimize flexible loads of ADN. The control problem is to compute the values of all the 0-1 variables at each time interval, which makes the power of loads follow a target to ensure the output of load function in a limited range. The target function is as:

$$\min J=\sum_{t=0}^{T-1} \|[p_1 \quad p_2 \quad \dots \quad p_m \quad \dots \quad p_j]\boldsymbol{\delta}(t)-P_f\|^2 \tag{11}$$

where p_m is the power of the control state of load m; and P_f is the power target of load. Then, the optimal state switching mode of flexible loads and the processing procedure of control information are obtained.

The MPC method of ADN flexible load is realized by receding horizon optimization (RHO) in [16], [17]. However, when the information processing is added, the control information is not switched at regular intervals. If the RHO is used, the intervals between two control periods are not equal. On the other side, it is unreasonable to process only the first control information of a control period, because this would break the spatio-temporal relationship of all the control information in the period. Thus, the MPC method used in this paper is just periodical optimization. Figure 5 illustrates the MPC program of ADN flexible load considering information flow.

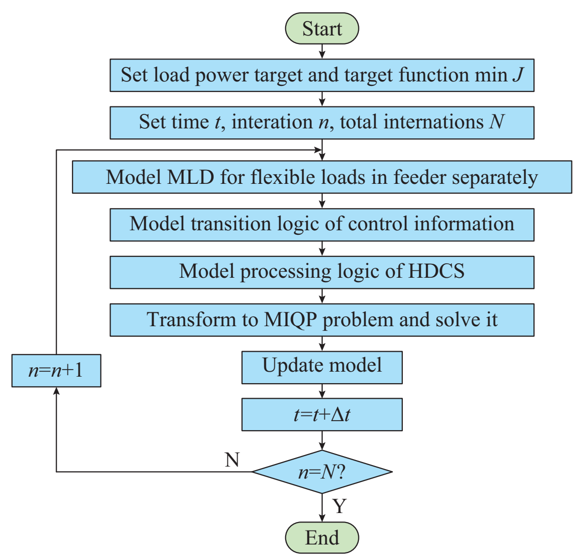

Fig. 5. Block diagram of MPC for ADN flexible load considering information flow.

According to the prediction of power output of DGs in ADN, the power target of flexible loads and the target function can be obtained at first. Then, the MLD of flexible load, control information transition and HDCS process can be modeled. After transforming MLD to MIQP problem, all the 0-1 variables are solved and the control information can be executed on the loads. Finally, the model for next control period is updated.

IV. Case Study

In this section, the flexible load model of ADN for refrigerator in [16], [17] is taken as an example to be controlled with two kinds of HDCS. Table II shows the parameters of flexible loads. The control target is to maintain the total power consumption at 356 kW on the condition that the inner temperatures of all loads are kept up within the limited range. Here, the parameter matrix $\boldsymbol{B}$ of (1) represents the comprehensive influence caused by outside heat disturbance and refrigeration in each load operation modes. According [16] and [17], (1) can be expanded as (11):

$$\begin{aligned}\boldsymbol{x}(t+1)=\boldsymbol{A}\boldsymbol{x}(t)+[&\boldsymbol{B}_1(t)+\boldsymbol{B}_2\boldsymbol{u}_1 \quad \boldsymbol{B}_1(t)+\boldsymbol{B}_2\boldsymbol{u}_2 \quad \dots \\ &\boldsymbol{B}_1(t)+\boldsymbol{B}_2\boldsymbol{u}_m \quad \dots \quad \boldsymbol{B}_1(t)+\boldsymbol{B}_2\boldsymbol{u}_j]\boldsymbol{\delta}(t)\end{aligned} \tag{12}$$

where $\boldsymbol{B}_1(t) = [B_{11}(t), B_{12}(t), \dots, B_{1n}(t)]^{\mathrm{T}}$ is the outside disturbance which will affect the function index at time $t+1$; and $\boldsymbol{B}_2$ is the refrigeration effect coefficient matrix of the $\boldsymbol{u}(t)$.

TABLE II
PARAMETERS OF FLEXIBLE LOADS IN THREE REFRIGERATORS

Load	Type (ton)	Element of $\boldsymbol{A}$	p_m (kW)	$\boldsymbol{x}(t)$ (°C)	Initial temperature (°C)	Element of $\boldsymbol{B}_1$ (°C)	Element of $\boldsymbol{B}_2$
1	1000	0.99	122	[−1, 1]	0	0.1	−0.24
2	2000	0.98	234	[−5, −3]	−4.0	0.2	−0.36
3	2500	0.97	370	[−1.5, 0.5]	−0.5	0.3	−0.50

The initial operation states of three loads are $[1, 1, 0]^{\mathrm{T}}$, that is only Load 1 and Load 2 are working, and the total power is 356 kW at this time.

A. Case 1: Loads in Different Control Areas

Figure 6 shows the HDCS structure of flexible loads in different control areas. The GEMS computes the operation states of three loads, and sends the control information to each load separately. Hence, the computation and control process of the three loads are independent. This means that the control information of each load is determined by different control information state and HDCS state. Therefore, the control information state vector $\boldsymbol{s}(t)$ and the HDCS state vector $\boldsymbol{c}(t)$ should be set, respectively.

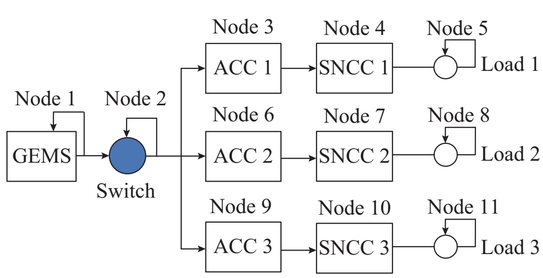

Fig. 6. HDCS structure of flexible loads in different control areas.

Assume that the controllers and the transmission nodes 2, 3, 4, 6, 7, 9, 10 can process only one control information at the same moment, thus the variable w in (8) is set as 1. Set the control step $\Delta t = 0.4$ s, and the control period $T = 24$ s. It means that there are 60 steps in one period. Since the control information from GEMS to each load goes through at least 4 HDCS nodes, and spends $4\Delta t$, the number of control information switching is set as $s = 15$.

Figures 7 and 8 show the inner temperatures of 3 refrigerators which are controlled by the MLD model and MPC method in [16]. Without information flow, the control process is not affected by HDCS, and all the operation effects of loads meet the demand. At each moment, the inner temperatures are all in the limited range, and the power consumption can be preferably maintained at the target of 356 kW.

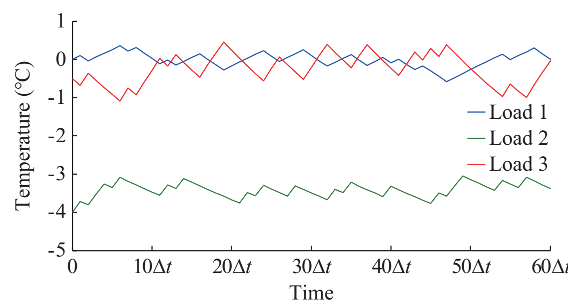

Fig. 7. Temperature of refrigerator loads in ADN without information flow in case 1.

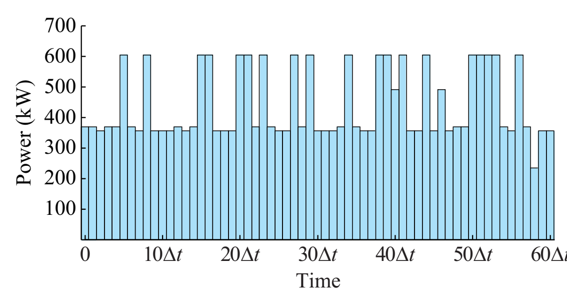

Fig. 8. Power consumption of ADN flexible loads without information flow in case 1.

When the information flow of HDCS is added, the inner temperatures of 3 refrigerators are shown in Fig. 9. Although the information procedure expends time in the controllers of HDCS and the same control information may be executed on the load for more time steps, the feasible solution is still obtained, and the inner temperatures of three refrigerators are restricted in the range.

Compared with Fig. 7, the times of adjusting temperature are obviously reduced. This is not only caused by the limit of state switching times of control information, but also the time delay of information process. Meanwhile, the adjusting restriction leads to the sharp fluctuation of temperature, and the temperatures are more liable to be out of range. Figure 10 shows the total power consumption of three loads considering information flow. For most of the time, the power consumption is kept near 356 kW, though the maximum value is up to 723 kW.

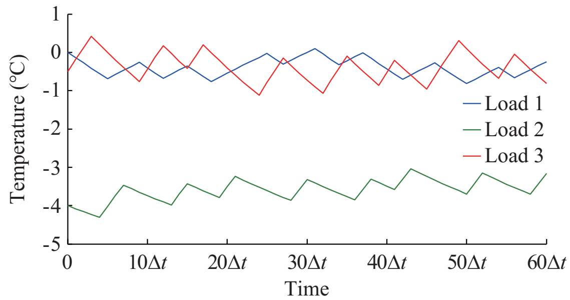

Fig. 9. Temperature of refrigerator loads in ADN considering information flow in case 1.

Compared with Fig. 8, the ability of target maintenance of Fig. 10 is insufficient, and this is caused by two aspects of influence: ① the sharp fluctuation of inner temperature makes the loads to switch between operation modes of great consuming gap; ② although the target function is designed to optimize the total power consumption of each step in a control period, it is difficult to get the optimal result like Fig. 8 due to the different arrival time and execution time of control information for the three loads.

Tables III-V list the procedure of 15 control information for three loads in HDCS. It can be seen that: ① all the control information is processed by corresponding controllers and allocated to loads; ② information of three loads all stays in node 2, for example, s_6 of Load 1 stays at node 2 when $t=18\Delta t$, and it is not sent to node 6 immediately; ③ except the GEMS and load, other HDCS nodes process only one control information; ④ the information does not stay at the ACC and SNCC more than one step. Hence, the information procedure satisfies all constraints.

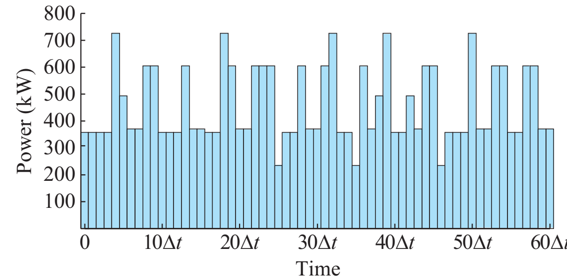

Fig. 10. Power consumption of ADN flexible loads considering information flow in case 1.

B. Case 2: Loads in the Same Control Area

In HDCS as shown in Fig. 11, all the loads locate in the same control area, and are controlled by the same SNCC. Different from the study case in Section IV-A, three loads in this case are dependent and can be processed as a single object. Thus, unified $\boldsymbol{s}(t)$ and $\boldsymbol{c}(t)$ should be set for state variables of control information and HDCS of all 3 loads.

TABLE III
TRANSFER TIME OF CONTROL INFORMATION FOR LOAD 1

Node	Transfer time														
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}
2	$3\Delta t$	$6\Delta t$	$10\Delta t$	$13\Delta t$	$15\Delta t$	$21\Delta t$	$25\Delta t$	$29\Delta t$	$30\Delta t$	$33\Delta t$	$38\Delta t$	$43\Delta t$	$46\Delta t$	$50\Delta t$	$54\Delta t$
3	$4\Delta t$	$7\Delta t$	$11\Delta t$	$14\Delta t$	$16\Delta t$	$23\Delta t$	$26\Delta t$	$30\Delta t$	$31\Delta t$	$34\Delta t$	$39\Delta t$	$45\Delta t$	$48\Delta t$	$52\Delta t$	$55\Delta t$
4	$5\Delta t$	$8\Delta t$	$12\Delta t$	$15\Delta t$	$17\Delta t$	$24\Delta t$	$27\Delta t$	$31\Delta t$	$32\Delta t$	$35\Delta t$	$40\Delta t$	$46\Delta t$	$49\Delta t$	$53\Delta t$	$56\Delta t$
5	$6\Delta t$	$9\Delta t$	$13\Delta t$	$16\Delta t$	$18\Delta t$	$25\Delta t$	$28\Delta t$	$32\Delta t$	$33\Delta t$	$36\Delta t$	$41\Delta t$	$47\Delta t$	$50\Delta t$	$54\Delta t$	$57\Delta t$

TABLE IV
TRANSFER TIME OF CONTROL INFORMATION FOR LOAD 2

Node	Transfer time														
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}
2	$2\Delta t$	$4\Delta t$	$9\Delta t$	$12\Delta t$	$16\Delta t$	$17\Delta t$	$26\Delta t$	$27\Delta t$	$32\Delta t$	$34\Delta t$	$37\Delta t$	$39\Delta t$	$48\Delta t$	$49\Delta t$	$55\Delta t$
6	$3\Delta t$	$5\Delta t$	$10\Delta t$	$13\Delta t$	$17\Delta t$	$19\Delta t$	$27\Delta t$	$28\Delta t$	$33\Delta t$	$35\Delta t$	$38\Delta t$	$42\Delta t$	$49\Delta t$	$50\Delta t$	$57\Delta t$
7	$4\Delta t$	$6\Delta t$	$12\Delta t$	$14\Delta t$	$18\Delta t$	$20\Delta t$	$28\Delta t$	$29\Delta t$	$34\Delta t$	$36\Delta t$	$39\Delta t$	$43\Delta t$	$50\Delta t$	$51\Delta t$	$58\Delta t$
8	$5\Delta t$	$7\Delta t$	$13\Delta t$	$15\Delta t$	$19\Delta t$	$21\Delta t$	$29\Delta t$	$30\Delta t$	$35\Delta t$	$37\Delta t$	$40\Delta t$	$44\Delta t$	$51\Delta t$	$52\Delta t$	$59\Delta t$

TABLE V
TRANSFER TIME OF CONTROL INFORMATION FOR LOAD 3

Node	Transfer time														
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}
2	$1\Delta t$	$5\Delta t$	$7\Delta t$	$11\Delta t$	$14\Delta t$	$20\Delta t$	$24\Delta t$	$28\Delta t$	$31\Delta t$	$35\Delta t$	$36\Delta t$	$42\Delta t$	$45\Delta t$	$52\Delta t$	$53\Delta t$
9	$2\Delta t$	$6\Delta t$	$9\Delta t$	$12\Delta t$	$15\Delta t$	$21\Delta t$	$25\Delta t$	$29\Delta t$	$32\Delta t$	$36\Delta t$	$37\Delta t$	$43\Delta t$	$46\Delta t$	$53\Delta t$	$54\Delta t$
10	$3\Delta t$	$7\Delta t$	$10\Delta t$	$13\Delta t$	$16\Delta t$	$22\Delta t$	$26\Delta t$	$30\Delta t$	$33\Delta t$	$37\Delta t$	$38\Delta t$	$44\Delta t$	$47\Delta t$	$54\Delta t$	$55\Delta t$
11	$4\Delta t$	$8\Delta t$	$11\Delta t$	$14\Delta t$	$17\Delta t$	$23\Delta t$	$27\Delta t$	$31\Delta t$	$34\Delta t$	$38\Delta t$	$39\Delta t$	$45\Delta t$	$48\Delta t$	$55\Delta t$	$56\Delta t$

Set $w = 1$ to restrict the capability of nodes 2, 3, and 4. The control step and control period are still set as $\Delta t = 0.4$ s and $T = 24$ s, respectively. Assume that the switching number of control information is 15. The inner temperature variation is shown in Fig. 12. The adjusting time is less than that in Fig. 9, but the adjusting amplitude increases.

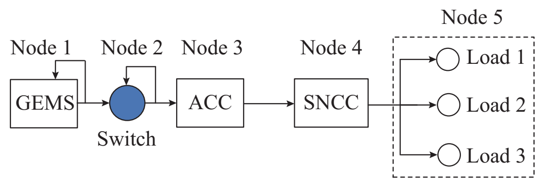

Fig. 11. Control system structure of flexible loads in the same control area.

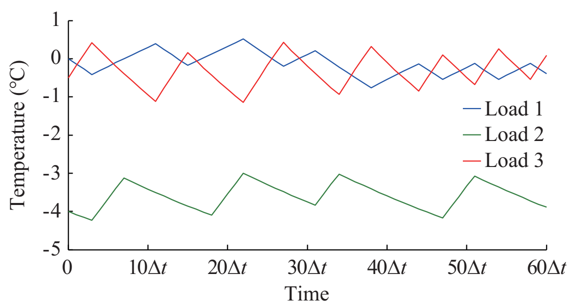

Fig. 12. Temperature of refrigerator loads in ADN without information flow in case 2.

This phenomenon is concerned with different HDCS structures. In this case, control information of each moment includes operation states of the three loads, and is sent to each load at the same time. Therefore, only when the information of different values is executed on loads, the operation state of loads may change. In Section IV-A, the temperature changes when any load changes its state.

Figure 13 shows the total power consumption of loads in case 2. Compared with Fig. 10, the switching time of load state reduces significantly, and the power can be kept near 356 kW.

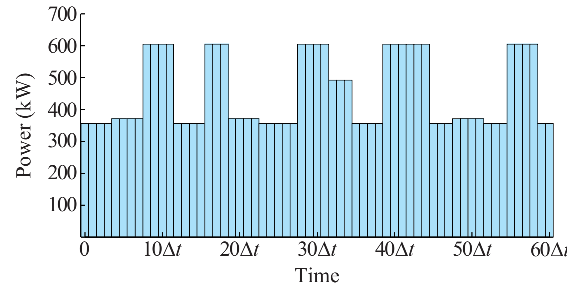

Fig. 13. Power consumption of ADN flexible loads considering information flow in case 2.

Table VI lists the procedure of 15 control information of HDCS in a control period. The 3 loads are treated together, thus only a group of information is obtained. Compared with Tables IV and V, ① the information process in this HDCS structure is more incompact and the time difference of information arrival and execution is more abundant; ② the control information stays at node 2 for more time, moreover, the information s_{10} is not transmitted to node 2 immediately after s_9 is handled in ACC, and it stays at node 1 for longer time. The reason for this phenomenon is that the demand for control information of loads is reduced. In Section IV-A, any load may change state independently at any time which causes state switching of other loads. Thus, the HDCS structure of Section IV-A has a higher requirement to the proceeding speed and frequency of information, and the situation of staying at the cycle nodes like GEMS and node 2 is infrequent.

Table VII lists the power consumption of three study cases.

TABLE VI
TRANSFER TIME OF CONTROL INFORMATION OF FLEXIBLE LOADS

Node	Transfer time														
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}
2	$1\Delta t$	$2\Delta t$	$5\Delta t$	$10\Delta t$	$11\Delta t$	$15\Delta t$	$24\Delta t$	$26\Delta t$	$28\Delta t$	$30\Delta t$	$35\Delta t$	$42\Delta t$	$44\Delta t$	$45\Delta t$	$53\Delta t$
3	$2\Delta t$	$5\Delta t$	$10\Delta t$	$11\Delta t$	$13\Delta t$	$16\Delta t$	$25\Delta t$	$28\Delta t$	$29\Delta t$	$35\Delta t$	$40\Delta t$	$43\Delta t$	$45\Delta t$	$49\Delta t$	$56\Delta t$
4	$3\Delta t$	$6\Delta t$	$12\Delta t$	$12\Delta t$	$14\Delta t$	$17\Delta t$	$26\Delta t$	$29\Delta t$	$30\Delta t$	$36\Delta t$	$41\Delta t$	$44\Delta t$	$46\Delta t$	$50\Delta t$	$57\Delta t$
5	$4\Delta t$	$7\Delta t$	$13\Delta t$	$13\Delta t$	$15\Delta t$	$18\Delta t$	$28\Delta t$	$30\Delta t$	$31\Delta t$	$37\Delta t$	$42\Delta t$	$45\Delta t$	$47\Delta t$	$51\Delta t$	$58\Delta t$

TABLE VII
COMPARISON OF POWER CONSUMPTION OF FLEXIBLE LOADS

HDCS	Power consumption (kWh)	Maximum load difference (kW)	Root mean square (kW)	Target deviation (%)
Not considered	2.9780	248	454.0477	27.54
In different areas	3.0858	370	475.8808	33.67
In same area	3.0160	248	462.9165	30.03

If information process is not considered, the control effect is obviously the best no matter what the HDCS structure is. However, HDCS and its information process truly bring negative influence to the primary device, and the best way is to optimize the control problem and dilute the influence. It can also be found from Table VII that loads in one control area operate better than loads in different areas, and the more complex the structure is, the greater the influence is.

V. Conclusion

ADN control function is based on HDCS. The existing researches mostly focus on the control of the primary system, and seldom pay attention to the influence brought by HDCS to primary devices.

To solve this problem, a CPS model for HDCS is studied. The information flow of ADN control process is analyzed, and the impact of HDCS is concluded from several aspects. The hybrid system based ADN model is built considering information flow, which includes primary device model, control information model, and HDCS model. An MPC method for ADN control is also formed based on this model.

After considering HDCS information flow in modeling and control of ADN, the energy flow of power system and information process of HDCS are integrated. The ADN control process not only optimizes the operation of primary devices, but also optimizes the working modes and time sequences of HDCS.

The modeling and control methods are tested in a case study of ADN flexible load. The simulation result shows that:

1) HDCS not only helps the primary system to realize control target but also brings adverse influence, and different HDCS structures lead to different influences. This indicates that the model of this paper represents the main properties of HDCS correctly.

2) Although HDCS has adverse effects on the primary system, the control target can still be optimized as far as possible. This indicates that the control method of this paper can eliminate the disadvantages of HDCS to an extent.

It can be seen from the test example that the models of this paper successfully integrate the information and physical performance of ADN control process. However, some operation details of ADN are still not contained, and models should be refined to fit more complex scenarios and devices, which will be considered in the future work.

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