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Zhang, Y, Fei, M, Sun, Q et al. (3 more authors) (2022) Letter: A multi-objective and multi-constraint optimization model for cyber-physical power systems considering renewable energy and electric vehicles. IEEE/CAA Journal of Automatica Sinica. ISSN 2329-9266

https://doi.org/10.1109/JAS.2022.106037

Letter

A Multi-Objective and Multi-Constraint Optimization Model for Cyber-Physical Power Systems Considering Renewable Energy and Electric Vehicles

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Dear editor,

To tackle the global challenges of climate change and energy security, building low carbon energy systems has become a research hotspot. Cyber-physical power systems (CPPSs) is an important infrastructure to link both energy and transport systems, two major sectors that are difficult to decarbonize, and it is necessary to establish CPPSs model to consider the integration of both renewable energy and electric vehicle (EV).

It is often extremely challenging to describe the topological structure of CPPSs due to their topological complexities and scales. The aim of this letter is to establish an optimization model with multi-objective and multi-constraint by considering renewable energy and EV. Firstly, the topological structure and the coupling characteristics of power grid and communication network for CPPSs are analyzed. Secondly, to formulate the optimization indexes of power grid and communication network, multiple control objectives are established. The coupling relationship between CPPSs layers is also described and analyzed. Thirdly, the interior point method and fminbnd function are used to solve multi-objective functions. Finally, experimental results confirm that this model can achieve precise control from both power grid and communication network.

Related work: CPPSs aim to intelligently integrate the behaviors and actions of all stakeholders in energy supply chain to efficiently deliver sustainable, economic, and secure electric energy. To make energy supply more flexible, portable and safer, CPPSs control must enhance the cooperation and interaction between power grid and communication network [1-2]. EV charging model in CPPSs is established [3], but the impact of power generation fluctuations from renewable sources on power system operation is not considered. Multi-objective optimization models are established [4]. These models are employed to realize power flow control and improve power quality. However, most of these models only consider single objective, while real power grid model needs to meet multiple different control objectives. A CPPS conceptual is established based on the concepts of complex network theory [5], which however does not provide mathematical models for CPPSs that can be used for the optimization purpose. State space models of CPSs are developed [6-7], which provided mathematical representations of dynamic behavior and structural characteristics of CPSs, but these models lack physical meanings, hence it is difficult to yield meaningful results.

Table I. Comparison of the Proposed and Related Energy Models

	Renewable energy	power grid	communication network	multi-objective	local optimal
[2-3]	√	√	X	√	X
[4]	X	√	X	√	X
[5]	X	√	√	X	X
[6-7]	X	√	√	X	√
Proposed model	√	√	√	√	X

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Motivated by the above observations, this letter proposes a model for CPPSs, where Table I. summarizes the features of the proposed model in comparison with the existing models.

Problem statement: A typical CPPS configuration is shown in Fig.1.

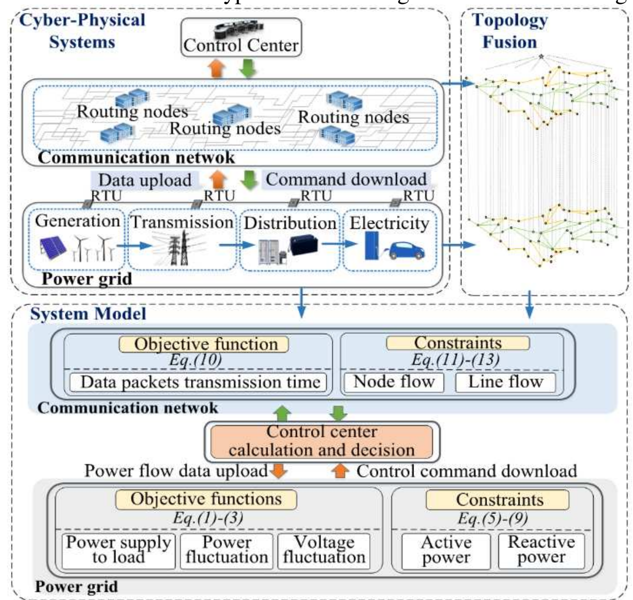


Fig. 1. The whole process of CPPSs modeling.

For CPPSs modeling, the existing challenges are summarized as follows:

(1) It is difficult to describe the topological relationship and coupling characteristics among different components of CPPSs due to sheer system complexity and scale. Most of the existing researches only considered the optimization objectives of power grid such as voltage and power, and the optimization indicators of communication network such as time delay, bandwidth are barely considered. The control objectives and objects are different between different layers, but they are coupled, which makes system optimization become a multi-objective optimization problem. How to establish a suitable multi-objective and multi-constraint optimization model for CPPSs is still a challenge.

(2) It is a difficult to analyze the relationship between different layers of CPPSs model and to achieve multi-objective optimization. Some coupling models are established by using state equations, ignoring the physical significance of system control variables. Due to complex structure of CPPSs, multi-objective solution of the model is a non-linear problem, which has a large number of control variables. How to choose the appropriate solution methods is another challenge.

Nomenclature

u_{imax}/u_{imin}	the upper and lower limits of voltage of the node i
$u_i(t)/h(t)$	voltage value of node i /system frequency at time t
$P_{Di}(t)/Q_{Di}(t)$	active/reactive power consumed by load node i
$P_{EVi}(t)$	active power supplied by the EV node i at time t
N_0	the number of nodes except the balance node
N_G/N_B	the number of generating nodes/ total number of nodes
$S_{i,v}$	communication flow from node i to node v
N_v	the number of communication sources located at node v
$S_v(k)$	communication flow of the group k information source injection system located at node v
M_v	the number of communication flows terminated at node v
$O_v(k)$	flow of group k terminated at node v
B_l/S	bandwidth in line l/ communication flow
d_i	the shortest path length between node j and target node.
c_i	queue length of the neighbor node j
h_d	control coefficient for routing policy
β	routing probability control coefficient
C_v	the maximum information exchange capacity

Proposed CPPSs model:

Power grid

1) Objective function and constraints: In CPPSs, the popular renewable power generation equipment include wind generators and photovoltaic generators. The relationship between wind speed and light intensity with output power are given by [8].

Under the load level for a period of time, the grid needs to supply power to all the loads including EVs. The total power supply demand of the entire grid A_{P_D} within a certain time T is given as

$$maxF_1\left(A_{P_D}(t)\right) = \int_{t=0}^{t=T} \sum_{t=1}^{N_D} x_i(P_{Di}(t) + P_{EVj}(t))\,dt \tag{1}$$

where x_i is used to represent the power supply status of the load node i or EV node j, and $x_i = 1$ implies supplying power to the load or EV while $x_i = 0$ implies no power supply.

Operating voltage of the entire CPPS needs to be close to the rated voltage, and cannot exceed the upper and lower limits of the voltage. It follows that

$$minF_2\big(u(t)\big) = \sum_N \int_{t=0}^{t=T} |u_i(t) - 1|dt \tag{2}$$

$$minF_3\big(u(t)\big) = \sum_N \int_{t=0}^{t=T} max\left((u_i(t) - u_{imax}), (u_{imin} - u_i(t)), 0\right) dt \tag{3}$$

The frequency of each node in the entire CPPS is assumed to have the same value. Therefore, the frequency requirement is

$$minF_4\big(h(t)\big) = \int_{t=0}^{t=T} |h(t) - 50|dt \tag{4}$$

Equality constraints of power grid are given by

$$P_{Wi}(t) + P_{Pi}(t) - P_{Di}(t) - P_i(e,f) = 0, i \in [1, N_0] \tag{5}$$

$$Q_{Wi}(t) + Q_{Pi}(t) - Q_{Di}(t) - Q_i(e,f) = 0, i \in [1, N_0] \tag{6}$$

where, $P_i(e,f)$ and $Q_i(e,f)$ are active and reactive powers of the node i respectively, and it is assume that $P_i = f(u_i)$.

Inequality constraints of power grid are given by

$$P_{Gi}^{min} \le P_{Gi}(t) \le P_{Gi}^{max}, i \in [1, N_G] \tag{7}$$

$$Q_{Gi}^{min} \le Q_{Gi}(t) \le Q_{Gi}^{max}, i \in [1, N_G] \tag{8}$$

$$U_i^{min} \le U_i(t) \le U_i^{max}, i \in [1, N_B] \tag{9}$$

where the value of $P_{Gi}(t)$ and $Q_{Gi}(t)$ should be within the set upper and lower limits. Voltage $U_i(t)$ should also lie within the set range.

2) Objective function solution of power grid: For the proposed model, considering dynamic change of power grid optimization index, multi-objective and multi-constraint problem can be solved by using the interior point method.

Communication network

1) Topology of communication network: For communication network topology, based on complex network theory, it can be described as a connected graph composed of nodes and edges. The set of nodes and edges denoted as E and D, respectively. Node connection relationship is represented by adjacency matrix A. The order of the matrix is equal to the number of nodes. If the nodes are connected, the corresponding element in A_{mn} and A_{nm} is 1, otherwise 0.

2) Objective function and constraints: The randomly generated small world network can be regarded as the communication network of CPPSs [5].

Four kinds of time delay considered in communication network: the processing delay t_p of package from node i to node v, queue delay t_q for package n, transmission delay t_r of each package, propagation delay t_l of packages propagating along l lines. The objective function of the total transmission delay as follows

$$minF_5\big(D(t)\big) = \sum_{p=i}^{v} t_p + \sum_{q=1}^{n} t_q + \sum_{r=1}^{m} t_r + \sum_{l=1}^{l} t_l \tag{10}$$

For any node $v \in E$, it is equal for in or out communication flow, and the incoming flow cannot be greater than the upper limit of its communication exchange capacity, i.e.,

$$\sum_{(i,v)\in E} S_{i,v} + \sum_{k=1}^{N_v} S_v(k) = \sum_{(v,j)\in E} S_{v,j} + \sum_{k=1}^{M_v} O_v(k) \tag{11}$$

$$0 \le \sum_{(i,v)\in E} S_{i,v} + \sum_{k=1}^{N_v} S_v(k) \le C_v \tag{12}$$

where $(i,v) \in E, (v,j) \in E$ represent that nodes i and j directly connected with node v. For any line $l \in D$, the rate of flow should be within the B_l, i.e.,

$$0 \le S_l \le B_l \tag{13}$$

Then, the packets format and delivery path are set by the power grid requirement. Firstly, whether the destination node of data packet is in the neighbor node need be determined, if yes the transmission is completed. Secondly, the probability P_j of each neighbor node being selected is calculated by the routing strategy. Thirdly, the next neighbor node is selected in term of the probability P_j, and data packet is transmitted to the neighboring node. Finally, the above procedure is repeated until the target node receives the packet. The center can process data packets without limit, other nodes can only process one data packet at a time and follow the principle of first-in-first-out. Routing protocol adopts the shortest path first strategy.

For a data packet to be transmitted, from node i, the set of neighboring nodes is E_i, then the effective distance H_j from the neighboring node $j \in E_i$ to the target node is

$$H_j = h_d d_j + (1 - h_d)c_j \tag{14}$$

According to H_j, the probability P_j of node i being selected is

$$P_j = e^{-\beta H_j} / \sum_{m\in L_i} e^{-\beta H_m} \tag{15}$$

3) Objective function solution of communication network: The fminbnd function is used to solve the shortest transmission time of communication network.

Coupling relationship:

1) Topological coupling: The coupling of two layers in topology can be described by "Degree-Degree". Degree k_i of node i is defined as the total number of edges directly connected to the node. Then, the degrees of power grid nodes and communication network nodes are ranked by ascending order, if the degree number are same, they are sorted by node number. Topological sets for two layers are N_p and N_c, The coupling of two sets is defined as

$$f_t: N_p \to N_c \tag{16}$$

2) Data coupling: Power gird nodes exchange data through communication network. Power grid generate or receive these data, while communication network focus on the smooth transmission of these data as shown in Fig. 2.

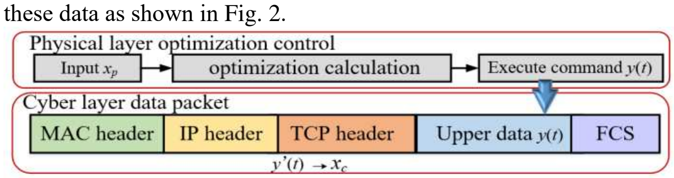


Fig. 2. Data fusion in power grid and communication network.

The input of power grid is x_p, and the output $y(t)$ is obtained through center calculation. Data package $y'(t)$ containing content $y(t)$. Content of $y'(t)$ is the execution command of power grid, while $y'(t)$ is transmitted via communication network. x_c is the input of communication network. It can be expressed as a map mapping of this process, which is defined as

$$f_1:\ x_p \to y(t) \quad f_2: y(t) \to y'(t) \quad f_3: y'(t) \to x_c \tag{17}$$

Therefore, each time an x_p is produced, and the process produces an x_c. The whole process can also be defined as

$$f_d: D_p \to D_c \tag{18}$$

where, D_p is a collection of power grid inputs, $x_p \in D_p$; D_c is the set of communication network inputs, $x_c \in D_c$.

CPPSs model: The model for CPPSs can be defined as

$$\begin{aligned} & minF_p(x_p,u,t) && minF_c(x_c,S,t) \\ & f_p(x_p,u,t) = 0 && f_c(x_c,S,t) = 0 \\ & g_p(x_p,u,t) = 0 && g_c(x_c,S,t) = 0 \\ & G_p(x_p,u,t) \le 0 && G_c(x_c,S,B,t) \le 0 \\ & f_t: N_p \to N_c && f_d: D(x_p) \to D(x_c) \end{aligned} \tag{19}$$

where F_p and F_c are the objective function, f_p and f_c are state equations, g_p and g_c are equality constraints, G_p and G_c are inequality constraints, , f_t and f_d are topological and data couplings. Relationship between this model with (1)-(13) is shown in Fig. 1.

Experiments:

Topology Establishment

1) Power grid topology: The experiment uses IEEE bus 9 topology.

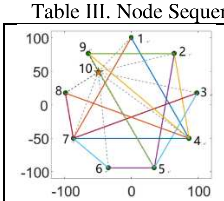
2) Communication network topology: A 9 node random small-world communication network is established as the green dot in Table III. left, nodes 1-9 are equivalent undifferentiated communication nodes, and node 10 is control node. In the nearest neighbor coupling network, half of the number of neighbor nodes is set to 0.5, and the probability of randomization plus one edge is set to 0.239.

Table II. Power Grid (P) Node Property

Node	1,2	3	5,6	7	4,8,9
Property	wind generators	photovoltaic generator	EV	Load	PQ node

3) Topological coupling: Node degree are sorted and then topology is coupled. The results are listed in Table III.

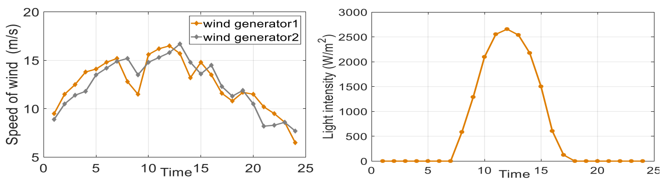
Table III. Node Sequence Number Changes Before and After Coupling



P		C		Coupling			
Node	Degrees	Node	Degrees	P	C	P	C
1,2,3	1	1,3,6,8	2	1-G1	1-C1	6-P5	2-C5
5,6,7	2	2,9	3	2-G2	3-C2	7-P6	9-C6
4,8,9	3	5	4	3-G3	6-C3	4-P7	5-C7
		4,7	5	5-P4	8-C4	8-P8	4-C8
						9-P9	7-C9

System operation process

The experimental parameters are from real physics laboratory. The wind speed and the light intensity received by the generators in 24 hours are shown in Fig. 3. The type of wind generator is FN2000L, and the type of the photovoltaic generator is Polycrystalline 260W. After modeling and parameter setting, the system flow chart is shown in Table IV.



(a) 24 hours wind speed. (b) 24 hours light intensity.

Fig. 3. Change of wind speed and light intensity within 24 hours.

Table IV. System Operation Process

I	1	Establish CPPSs model, and initialize the operating parameters.
P	2	Power requests from the EV and load, which change every hour within 24 hours. So $t = 1,2,3 \dots 24$;
	3	Generates data packets $pLoad_i$, pEV_i and $qLoad_i$, qEV_i of power requests for load and EV.
C	4	Packets upload.
	5	Control center receives the load and EVs request packets;
	6	According to power grid objective functions and constraints, control center obtains the output value P_{wi}, Q_{wi}, P_{Pi}, Q_{Pi} of the generators by performing optimal power flow calculation;
	7	Generates generators receive data packets and output power according to the calculation results of the previous step;
	8	Packets download.
P	9	Generator receives data packets and adjusts.
C	10	Whether the power grid operates stably after power flow calculation? If yes, jump to next step. If no, go to step 4.

1) Load input: Power required for the EV and load can be satisfied by the combined output of three generators. Assuming that the load changes once every hour, the requested power of EVs and load comes from a laboratory case, $\alpha = 0.9$.

2) Information transmission and optimization calculation: When the load and EV request changes, CPPS starts to operate according to Table IV. The parameters are set as $C_v = 12.5MB/S$, $B_{i,j} = 100M$, $t_p = 0.1\mu s$, $t_q = 0.05ms$, $t_r = 0.2ms$. Set each data package to have the same propagation time on each line $t_l = 0.1ms$. Then, the amount of data packets S_Z that need to be transmitted is calculated. The size of each packet is 1400 bytes.

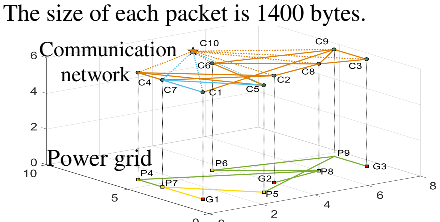


Fig. 4. A transmission process of CPPSs.

Here is an example of CPPs operation process in Fig. 4. For the power grid, P5 needs power supply, energy flowing from G1 to P5 needs to go through P7. But in the communication network, data packet transmission is shown in Table V.

Table V. One Case for Transports in Power Grid and Communication Network

P	G1 → P7 → P5			
C	C5→C10	C10→C7/C1	C1→C7→C5	C5 → C10

3) Generator power generation: The generator receives data packets passed by the center through communication network and executes power supply instructions, power output shown in Fig. 5.

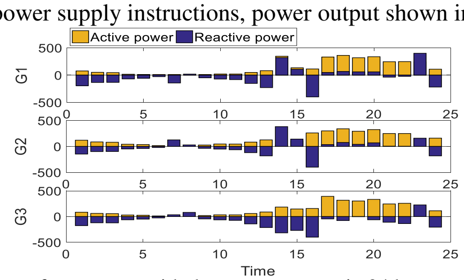


Fig. 5. Output of generators with the power request in 24 hours.

Data packet transmission time is shown in Fig. 6. It is found that the proposed CPPSs model guarantees faster transmission after optimization.

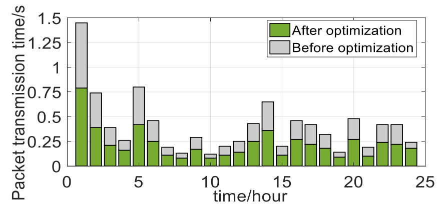


Fig. 6. Comparison of data packets transmission time.

Conclusions: This letter presents a multi-objective and multi-constraint optimization model for CPPSs considering renewable energy and EV. The interior point method and fminbnd function are used to find the multi-objective solution of the CPPS. To achieve the optimal operation, the coupling state of all layers must be considered and all layers of CPPSs must be optimized simultaneously. The proposed CPPSs model has been validated, which can be extended to the larger scale power systems in the future.

Acknowledgment: The work was supported by Project of Science and Technology Commission of Shanghai Municipality under Grant 19510750300, 21190780300 and 20JC1414000. 111 Project under Grant D18003. National Science Foundation of China under Grant 92067106.

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