Coordinated optimization of district electricity and heating system based on genetic algorithm

Hailin Ge
School of Electric Power
South China University of Technology
Guangzhou, China, 510641
e-mail: epgodspeed.cool@mail.scut.edu.cn

Haoyong Chen
School of Electric Power
South China University of Technology
Guangzhou, China, 510641
e-mail: eehychen@scut.edu.cn

Fei Liu
School of Electric Power
South China University of Technology
Guangzhou, China, 510641
e-mail: eeliufei@outlook.com

Cong Zhang
School of Electric Power
South China University of Technology
Guangzhou, China, 510641
e-mail: wanzhangcong@sina.com

***Abstract*—Interconnection and coupling between electric power, heating and natural gas systems are becoming closer and closer. From the point of view of coordinated optimization, through the establishment of mathematical model of district electricity and heating system, a coordinated optimization model of district electricity and heating system based on genetic algorithm is constructed in this paper. A typical district electricity and heating system in engineering is modelled and analyzed using the above mentioned model, the average convergence characteristics and optimization effect are studied. Through the experimental results, the practicability and validity of the coordinated optimization model of district electricity and heating system based on genetic algorithm are verified. The research contents of this paper lays the foundation for the operation optimization of district electricity and heating system.**

***Index Terms*--Electric power; district heating; optimization; genetic algorithm**

I. INTRODUCTION

The ever increasing energy and environmental crisis have given a big push for the development of distributed energy systems and energy internet [1]-[2]. The transmission and transformation between various forms of energy can be implemented by energy internet, whose core connotation is to realize large scale utilization and sharing of renewable energy, especially distributed renewable energy [3]. District electricity and heating system, which has a huge potential for energy saving, is being applied widely [4]. From the point of view of generality of different forms of energy, the energy network equation is established according to Energy Axiom and Transfer Axiom in [5]. It lays an important theoretical foundation for the energy analysis of district electricity and heating system. A hybrid power flow calculation method for district integrated energy system including electricity, gas and heat is proposed in [6]. Ref. [7] puts forward a decomposed and an integrated electrical-hydraulic-thermal calculation method for district electricity and heating system respectively.

The operation optimization of district electricity and heating system is usually carried out independently in the previous studies [8]-[9]. Optimal operation of integrated electric power and heating systems to accommodate the intermittent renewable sources in urban areas is investigated in [4]. Ref. [10] focuses on the study of multi-objective thermodynamic optimization and application of distributed combined cooling heating and power system. An operation optimization model of integrated electric power and heating systems considering heating network constraints and thermal unit commitment is proposed in [11].

Optimization problems of electric power and heating systems are usually discrete and nonlinear. Conventional solution methods for these problems include linear programming, nonlinear programming and quadratic programming etc. These methods usually require the assumption that control variables are continuous and objective function is differentiable, and only local optimal solutions can be achieved [12]-[15]. Genetic algorithm has been widely applied to the optimization problems of electric power and heating systems, due to its unique characteristics [16]-[19]. Compared with the traditional nonlinear programming method, genetic algorithm has better convergence, stronger adaptability and greater chance to obtain global optimal value.

This paper consists of three parts, which respectively are modelling of district electricity and heating system, construction of coordinated optimization model and application of genetic algorithm. Based on known conditions, the electric power system and heating system are modeled respectively. On the basis of the above model, taking the minimum total energy loss as objective function, combining with equality and inequality constraints in the system, coordinated optimization model of district electricity and heating system based on genetic algorithm is constructed. Taking a typical district electric power and heating system in engineering as research object, the above coordinated optimization model is used to model and analyze. The

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practicality and effectiveness of the proposed model and theory are discussed subsequently.

II. DISTRICT ELECTRICITY AND HEATING SYSTEM

District electricity and heating system can usually be divided into three parts: electric power system, heating system and coupled energy conversion equipment (such as cogeneration unit, heat pump, boiler and circulating pump, etc.). Through these coupled energy conversion equipment, direction and rate of energy flow can be controlled, and energy transfer of different forms between electric power system and heating system can be achieved. The schematic diagram of district electricity and heating system is shown in Figure 1.

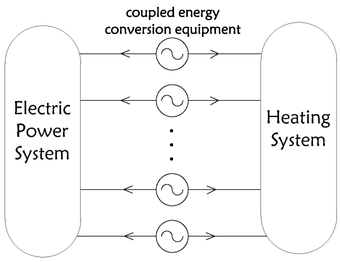

Fig. 1 Schematic diagram of district electricity and heating system

A. Electric power system

The power balance equation of electric power system is shown in the formula (1).

$$\begin{cases} P_{is} - V_i \sum_{j=1}^{N} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0 \\ Q_{is} - V_i \sum_{j=1}^{N} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0 \end{cases} \quad (1)$$

In formula (1), P_{is} and Q_{is} are respectively active and reactive power injected into node i ; N is the total number of nodes, i and j are node numbers ; V is voltage magnitude, θ is voltage phase angle, G and B are respectively the real and imaginary part of elements of node admittance matrix.

B. Heating system

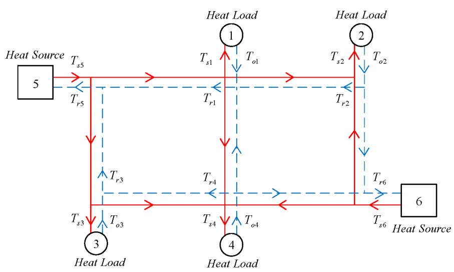

Fig. 2 Schematic diagram of heating system

The schematic diagram of heating system is depicted in figure 2, where there are two heat sources and four heat users. In figure 2, while red solid line represents heating supply network, blue dashed line represents heating return network; T_s , T_o and T_r are respectively supply temperature, outlet temperature and return temperature at different nodes.

Heating system can be modeled as formula (2). The equations in formula (2) subsequently are heat balance equation of heating system, pressure loop equation, supply temperature equation and return temperature equation.

$$\begin{cases} C_p \sum_{j=1}^{nhl} Ah_{ij} q_{mj} (T_{si} - T_{oi}) = Q_{hi} \\ \sum_{j=1}^{nhloop} R_{mj} q_{mj} \quad = 0 \\ \sum_{j=1}^{nhload} A_{sij} (T_{sj} - T_a) = b_{si} \\ \sum_{j=1}^{nhload} A_{rij} (T_{rj} - T_a) = b_{ri} \end{cases} \quad (2)$$

In heat balance equation, i and j are node number of heat loads and pipeline number of heating system respectively, nhl is the total number of pipelines, C_p is specific heat of hot water, Ah is incidence matrix of heating network, q_{mj} is mass quantity of pipeline j , Q_h is heat load; In pressure loop equation, j is loop number, $nhloop$ is total number of loops, R_{mj} is flow resistance of pipeline j . In hot water supply temperature equation and return temperature equation, i and j both are node numbers of heat loads $nhload$, T_a is environment temperature, A_s , A_r , b_s and b_r are supply and return temperature coefficient matrix of heat loads, A_s and A_r are constant matrix, matrix elements of b_s and b_r are the function of supply temperature of heat sources and outlet temperature of heat loads.

C. Coupled energy conversion equipment

For CHP units using gas turbines or internal combustion reciprocating engines, then the relation between heat and electrical power generation is simplified as equation (3), where c_m is the heat-to-power ratio, P is the electrical power output and ϕ is the heat output of CHP units.

$$c_m = \frac{\phi}{P} \quad (3)$$

For CHP units using steam extraction engines, the relation between heat and electrical power generation is simplified as equation (4), where P_{con} is the electrical power generation of the extraction unit in full condensing mode, Z is a constant.

$$Z = \frac{\phi}{P_{con} - P} \quad (4)$$

The consumed electrical power by a circulation pump is calculated as equation (5), where P_p is the electrical power consumed by a circulation pump; m_p is the mass flow rate through the pump; η_p is the efficiency of the pump; H_p is the pump head of the network.

$$P_p = \frac{m_p g H_P}{10^6 \eta_P} \quad (5)$$

D. District electricity and heating system power flow

Based on Newton iteration method, Ref. [7] proposed an integrated electrical-hydraulic-thermal calculation method for district electricity and heating system. In the integrated electrical-hydraulic-thermal calculation method, the unknown variables in district electricity and heating system are treated uniformly, using the augmented unbalance and augmented jacobian matrix to constantly revise.

III. COORDINATED OPTIMIZATION MODEL OF DISTRICT ELECTRICITY AND HEATING SYSTEM

A. Objective function

In the coordinated optimization model, the objective is to minimize the total energy loss of the system. Total energy loss of district electricity and heating system is:

$$Enloss = Eloss + Ploss + Hloss$$
$$\begin{cases} Eloss = \sum\limits_{i,j \in S_{el}} G_{ij}(V_i^2 + V_j^2 - 2V_i V_j \cos\theta_{ij}) \\ Ploss = 2 * \sum\limits_{i \in S_{hl}} R_{mi} q_{mi}^2 / \rho \\ Hloss = \sum Qh_{in} - \sum Qh_{out} \end{cases} \quad (6)$$

In formula (6), $Eloss$ represents line-loss of electric power system, S_{hl} is the set of branches in electric power system, i and j are both the node numbers of both ends of branches; $Ploss$ represents pressure energy loss of heating system (including supply and return networks) [5], S_{hl} is the set of pipelines in heating system, ρ is density of hot water; $Hloss$ represents heat loss of heating system, whose value is equal to the difference between the sum of input heat energy Q_{hin} and that of output heat energy Q_{hout}.

Considering that state variables may exceed limits in optimization process, a penalty function of state variables is added to the objective function [15]. The final form of the objective function is shown in formula (7), where λ is the penalty factor for state variable x (voltage amplitude V at load nodes, reactive power of generator Q_G, mass flow q_m, hot water supply temperature T_s at heat load nodes) that exceeds the limit.

$$\min F = Enloss + \sum \lambda_i \sum (\frac{x_j - x_{\min}}{x_{\max} - x_{\min}})^2 \quad (7)$$

B. Equation of equality constraint

As mentioned above, the power balance equation of electric power system, heat balance equation of heating system, pressure loop equation, the equations of hot water supply and return temperature are the basis of optimization problem of district electricity and heating system. Here, formula (1) and (2) in the upper section is restated in the form of matrix, where $\mathbf{S_{is}}$ is complex power matrix of electric power system.

$$\begin{cases} \mathbf{S_{is}} - \mathbf{V}(\mathbf{YV})^* = 0 \\ C_p \mathbf{A_h q_m}(\mathbf{T}_s - \mathbf{T_o}) - \mathbf{Q_h} = 0 \\ \mathbf{B_h R_m q_m} = 0 \\ \mathbf{A_s}(\mathbf{T_s} - T_a) - \mathbf{b_s} = 0 \\ \mathbf{A_r}(\mathbf{T_r} - T_a) - \mathbf{b_r} = 0 \end{cases} \quad (8)$$

C. Inequality constraints of control variables

Control variables of electric power system mainly includes the generator terminal voltage V_G, switchable shunt capacitor banks C, tap position of transformer Tap, control variables of the heating system is mainly hot water supply temperature at heat sources T_{Gs}. Inequality constraints of control variables of district electricity and heating system are shown as follows.

$$\begin{cases} V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max},\ i \in S_G \\ \mathrm{C}_i^{\min} \le C_i \le C_i^{\max},\ i \in S_C \\ Tap_i^{\min} \le Tap_i \le Tap_i^{\max},\ i \in S_{Tap} \\ T_{Gsi}^{\min} \le T_{Gsi} \le T_{Gsi}^{\max},\ i \in S_{hsource} \end{cases} \quad (9)$$

max and min are respectively the upper and lower limits of adjustment range of the control variable, S_G、S_C、S_{Tap} and $S_{hsource}$ are respectively the set of generating units, switchable shunt capacitor banks, tap positions of transformers and heat sources.

D. Inequality constraints of state variables

The state variables of electric power system mainly include the voltage amplitude V at load nodes, reactive power Q_G of generating units. The state variable of heating system mainly include mass flow q_m of pipelines and hot water supply temperature T_s at heat loads. Inequality constraints of state variables of district electricity and heating system are:

$$\begin{cases} V_i^{\min} \le V_i \le V_i^{\max},\ i \in S_{PQ} \\ Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max},\ i \in S_G \\ q_{mi}^{\min} \le q_{mi} \le q_{mi}^{\max},\ i \in S_{hl} \\ T_{si}^{\min} \le T_{si} \le T_{si}^{\max},\ i \in S_{hload} \end{cases} \quad (10)$$

where S_{PQ}, S_G, S_{hl} and S_{hload} are respectively the set of PQ nodes, generating units, pipelines and heat loads.

IV. APPLICATION OF GENETIC ALGORITHM IN COORDINATED OPTIMIZATION MODEL

Genetic algorithm is a random search algorithm based on natural selection and natural genetic mechanism. Genetic algorithm retains a set of candidate solutions in each iteration process; through individual evaluation and comparison, relatively good individuals were selected; using genetic manipulation like selection, crossover and mutation to combine the individuals selected, new candidate solutions will be generated; the processes above will be repeated until convergence [20].

Genetic algorithm has been widely used in the field of electric power system and heating system, because of its many advantages (such as global convergence, strong adaptability, etc.) [15]-[19]. In this paper, the coordinated optimization model of district electricity and heating system, in essence, is a large-scale nonlinear optimization problem. The application of genetic algorithm in this coordinated optimization model is shown in Figure 3, *Gen* represents iteration number of genetic algorithm

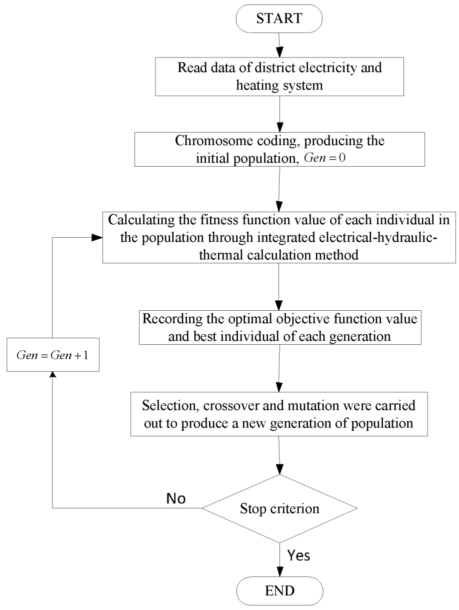

Fig. 3 Flow chart of application of genetic algorithm

V. EXAMPLE ANALYSIS

In this chapter, a typical district electricity and heating system in engineering will be taken as the research object, which will be modelled and analyzed using the coordinated optimization model. The program of this paper is implemented on the MATLAB software platform.

The district electricity and heating system is located on the island of Bali, the schematic diagram of which is shown in Figure 4 [7]. There are 9 buses and 5 concentrated loads in electric power system, 32 nodes and 32 pipelines in heating system. This district electricity and heating system is coupled together by three cogeneration units, which respectively are gas turbine CHP unit, extraction steam turbine CHP unit and reciprocating engine CHP unit.

It is necessary to select two nodes as slack nodes in the analysis of district electricity and heating system. In the case of this paper, the gas turbine CHP unit and extraction steam turbine CHP unit (unit 1 and unit 2) are respectively selected as the slack nodes of electric power and heating systems.

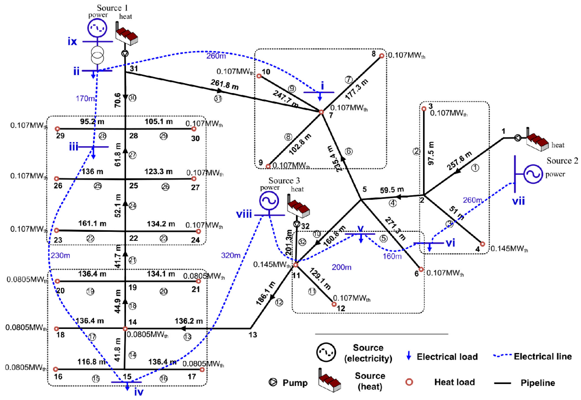

Fig. 4 A district electricity and heating system of Barry Island

As shown in Figure 4, the control variables of the system include the transformer tap position, voltage magnitude of units 1-3 and the hot water supply temperature. Unknown variables include voltage magnitude of electric power system at load node and voltage phase angle at all nodes except the slack node of electric power, the mass flow of pipelines in heating system and hot water supply temperature and return temperature at load nodes.

In the example of this paper, generations of genetic algorithm $T=60$ and population size in each generation $Popsize=40$.

A. *Average convergence characteristic*

For optimization calculation, the convergence characteristics of genetic algorithm in this optimization problem can be represented by the variation of objective function value of the optimal individual obtained in each generation. The average convergence of genetic algorithm in 100 optimization process is shown in Figure 5.

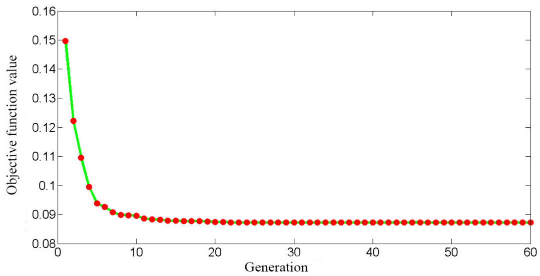

Fig. 5 Average convergence characteristics

It can be seen from Figure 5 that after about 20 iterations, the optimal solution is achieved. Genetic algorithm shows strong convergence ability and fast convergence speed in this optimization problem.

B. *Analysis of the optimization results*

Through the above experiments, the optimal individual minimizing objective function can be obtained. Under the control of the optimal individual, the variations of voltage magnitude and voltage phase angle, mass flow, supply and return temperatures before and after optimization are shown in figure 6-8, where green line represents system parameters before optimization and red solid point represents system parameters after optimization.

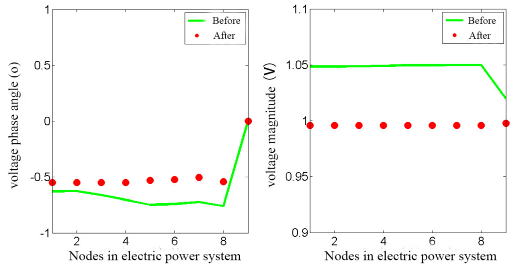

Fig. 6 Comparison of voltages before and after optimization

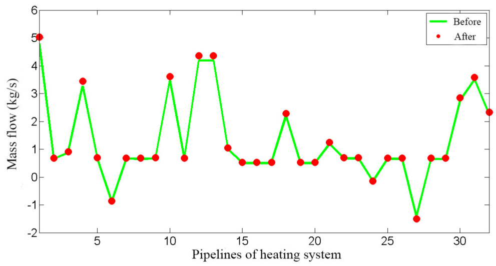

Fig. 7 Comparison of mass flows before and after optimization

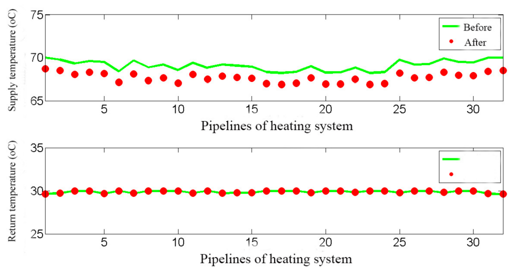

Fig. 8 Comparison of temperatures before and after optimization

From the above comparison, it can be known that the changes of the state parameters before and after optimization are little, all in the range of safe operation. For electric power system, voltage phase angle of each node tends to be 0 and voltage amplitude tends to be 1 after optimization, which is more favorable for the stable operation of power system. For heating system, mass flow in the pipeline increases and hot water supply temperature decreases, which is also more conducive to reduce the heat loss of the heating system. Compared with the original energy loss of $0.0951MW$ of the district electricity and heating system, the energy loss after optimization reduces to $0.0833MW$, the loss reduction ratio reaches 12.41%.

VI. CONCLUSION

In this paper, through the establishment of mathematical model of electric power system and heating system, with the goal of total energy loss reaches the minimum, with equality and inequality constraint system, the coordinated optimization model of district electricity and heating system based on genetic algorithm is constructed in this paper. The results of a numerical example show that the coordinated optimization model of district electricity and heating system based on genetic algorithm is correct, which is practical and effective in operation optimization of practical system. This paper lays the foundation for the study of the operation optimization of the district electricity and heating system.

REFERENCES

[1] W. Yiwu, W. Shilie, S. Ming. Distributed power system based on micro gas turbine. *Electric Power*, 36(3): 4-7, 2003.

[2] T. Shiming, L. Wenpeng, Z. Dongxia. Technical Forms and Key Technologies on Energy Internet. *Proceedings of the CSEE*, 14: 3482-3494, 2015.

[3] D. Zhaoyang, Z. Junhua, W. Fushuan. From Smart Grid to Energy Internet: Basic Concept and Research Framework. *Automation of Electric Power Systems*, 38(15): 1-11, 2014.

[4] J. Li, J. Fang, Q. Zeng. Optimal operation of the integrated electrical and heating systems to accommodate the intermittent renewable sources. *Applied Energy*, 167: 244-254, 2016.

[5] C. Haoyong, W. Junzhong, W. Zengyu. Transfer Laws and Equations of Energy Networks. *Journal OF Xi'An Jiaotong University*, 48(10): 66-76, 2014.

[6] X. Xiandong, J. Hongjie, J. Xiaolong. Study on Hybrid Heat-Gas-Power Flow Algorithm for Integrated Community Energy System. *Proceedings of the CSEE*, 14: 3634-3642, 2015.

[7] X. Liu, J. Wu, N. Jenkins. Combined analysis of electricity and heat networks. *Applied Energy*, 162: 1238-1250, 2016.

[8] Y. Juan. Optimization of urban central heating system. Tianjin: Hebei University of Technology, 2005.

[9] X. Lei, Z. Cong, C. Haoyong. Optimal Reactive Power Dispatch Considering Wind Turbine Systems. *South Power System technology*, 9(5): 76-81, 2015.

[10] W. Dawei. Multi objective thermodynamic optimization theory and application of distributed cold heat and power cogeneration system. Shanghai: Shanghai Jiao Tong University, 2008

[11] G. Zepeng, K. Chongqing, C. Xinyu. Operation Optimization of Integrated Power and Heat Energy Systems and the Benefit on Wind Power Accommodation Considering Heating Network Constraints. *Proceedings of the CSEE*, 14: 3596-3604, 2015.

[12] Z. Youxin, X. Guoyu. Calculation and Analysis of Optimal Control of System Voltage and Reactive Power by Sensitivity Methid. *Journal of Chongqing University*, 04: 1-11, 1985.

[13] L. Linchuan, X. Daozhi, Y. Zhenping. An Optimal Calculation of Voltage and Loss in Power System. *Automation of Electric Power Systems*, 07: 30-33, 1995.

[14] S. Rugang. Reactive Power Optimization in Power System Quadratic Programming Method. *Proceedings of the CSEE*, (5): 42-50, 1986.

[15] Z. Shuangxi, Y. Bin. A New Algorithm for Reactive Power Optimization – Genetic Algorithms. *Automation of Electric Power Systems*, 19(11): 19-23, 1995.

[16] M. Jintao, Y. Yihan. Application of Genetic Algorithms in Reactive Power Optimization. *Proceedings of the CSEE*, 05: 347-353, 1995.

[17] C. Haoyong, W. Xifan. A Genetic Algorithm with Annealing Selection for Reactive Power Optimization. *Electric Power*, 31(2): 3-6, 1998.

[18] Q. Xuzhong, J. Yi. Accessibility Analysis of District Heating loop-networks Based on Genetic Algorithms. *Journal of Tsinghua University(Sci & Tech)*, 39(6): 1-95, 1999.

[19] H. Xueqin. Study on heat distribution of the central heating network based on genetic algorithm. Shenyang: ShenYang Ligong University, 2012.

[20] J. H. Holland. *Adaptation in natural and artificial systems: An introductory analysis with applications to biology, control, and artificial intelligence*. Oxford: U Michigan Press, 1975.

[21] X. Xinyin, W. Yaowu. *Genetic algorithm and its application in electric power system*. Wuhan: Central China University of Science & Technology Press, 2002.