Resistance Identification in HVAC Distribution Networks Based on Collective Intelligence System

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***Abstract*—This paper introduces a new method for resistance identification in the HVAC distribution network based on a novel collective intelligence system. The proposed method implements the identification process by solving the basic energy and flow balance functions and exchanging information between neighboring nodes. The identification results are presented and the non-uniqueness problem is investigated. The necessary conditions to secure a unique solution are studied and the potential of using the proposed method for fault diagnosis of the HVAC system is discussed.**

Keywords—resistance, identification, CIS, distribution network, HVAC

I. INTRODUCTION

The HVAC system is responsible for over 40% of energy consumption for many types of buildings, making it one of the major energy consumers in the building sector [1]. The distribution network, which circulates the air or water and delivers the heat or cold across the HVAC system, plays an important role in system operation, control, and maintenance. The resistance information of the distribution network is not only crucial to the hydraulic and heat balance but also helpful for leakage detection and fault diagnosis. However, it is usually impractical to measure or monitor all the distribution network branches to get the required information in real engineering practices due to limited sensors or unreachable positions. Many estimation methods and optimization algorithms, therefore, have been proposed in previous researches to improve the practicability, efficiency, and accuracy of resistance identification and network calibration [2-7]. For instance, the Genetic Algorithm (GA) [8] and its upgraded version of GASCAA algorithm [9], were employed to search for the optimal solution that matches the calculated value as closely as possible to that of the real network. The RC^2 method [10] was developed for hydraulic fault diagnosis and parameter identification in district heating networks.

A decentralized identification method has been recently introduced to generate the overall description of the HVAC distribution system and calculate the pressures and flow rates [11]. The approach is based on a collective intelligent system (CIS) that uses standard smart nodes as identification and calculation units. Compared to the traditional centralized approach, the CIS method has been proved to be easy, robust, and feasible for building-level implementation.

This paper employs the concept of CIS to identify the resistance for the HVAC distribution network. By implementing the method on two different HVAC distribution typologies, the simulation results are provided and the non-uniqueness problem is investigated.

II. RESISTANCE IDENTIFICATION

A. Topology Description

The CIS is a decentralized, flat-structured building automation system controlled by standard distributed smart nodes, called CPN. All CPNs have identical structure, hardware, and software, and share equal relations. Each CPN represents a smart zone or a smart device and can only exchange information with its neighboring nodes. There is no central CPN that works as a higher-level coordinator or controller; therefore, the CIS can decentralize the HVAC distribution network into a flat-structured topology and enable the new system to self-identify, self-integrate, self-adapt and self-program [12].

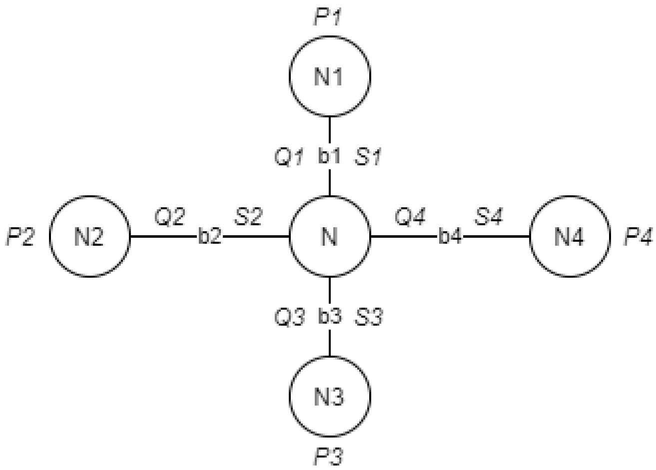

Fig. 1. A typical unit of an HVAC distribution network

Fig. 1 illustrates a simple topology of the HVAC distribution network under the CIS theory. The node may represent a space, a joint, a water or air intake or outlet, etc., depending on its inherent properties and position. The lines connecting the nodes represent ducts or pipes. One node may have multiple branches, and the node contains all its property information such as the pressure (P) at the node, and the resistance (S) and the flow rate (Q) of its branches. Through data exchange with its neighbors, each node can acquire the property information of its neighboring nodes. However, none of the nodes has the overall information about the entire network.

Each node is governed by both the flow balance function (1) and the energy balance function (2). For node N in Fig 1:

$$\sum_{i=1}^{n} Q_i = Q_N \tag{1}$$

Where Q_i is the flow rate of branch b_i; Q_N is the flow rate between node N and the ambient; n is the total number of neighboring nodes.

$$P_i - P_N = S_i Q_i^2 \tag{2}$$

Where P_i is the pressure of node N_i; P_N is the pressure of node N; S_i is the resistance of branch b_i.

B. Identification Process

The concept of CIS enables each node to store its property information and perform the flow balance and energy balance calculations locally. Meanwhile, by continually exchanging the calculated results with its neighbors, the node keeps refreshing its local information and proceeding the iteration with the updated knowledge. When the newly updated information is close enough to the previous one, the system tends to reach a steady-state globally in terms of energy balance and flow balance.

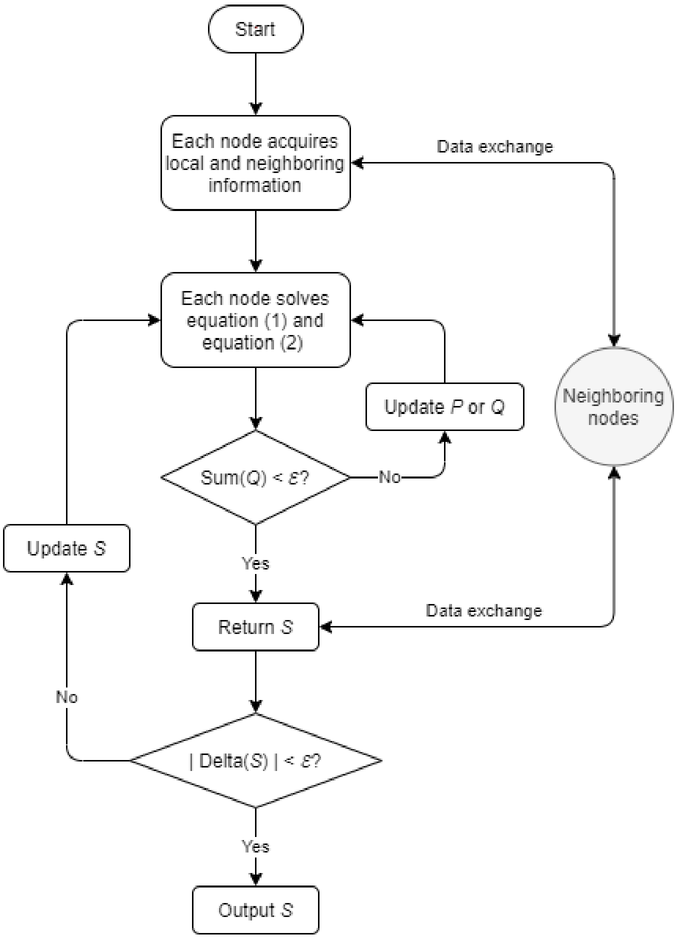

Fig. 2. Identification process

This principle is implemented in a CIS simulation platform programmed by Python to identify the resistance for HVAC distribution networks. As soon as the simulation is initiated, each node employs its local and neighboring information, assuming it is true, to carry out the flow balance and energy balance calculations by solving equation (1) and equation (2). When the algebraic sum of the inward (-) and outward (+) flow rates to the node is less than a given threshold, the flow balance is deemed to be achieved. Otherwise, an adjusted P or Q (depending on what is variable in practice) will be utilized for another iteration. The updated pressure and flow rate will be forwarded to its neighbors through data exchange, and the calculated resistance is then compared with the one that computed by its neighbor. The difference shall be close to zero since they share the same branch. If not, another energy balance and flow balance iteration will be enabled with an updated S. A leaning factor of 0.5 is used to decide how much of the new information will be used to update the previous knowledge. The identification process continues until the newly calculated information is close enough to the previous one, indicating that the estimation is precise enough. This calculation algorithm is illustrated in Fig. 2.

III. Results and Discussions

The proposed method was first applied to a simple air distribution network with 5 nodes as shown in Fig. 3. When the pressure at each node and the flow rate in each branch are all given, the resistance can be straightforwardly determined via equation (2). However, measuring and monitoring all pressures and flow rates are usually not practical in real engineering practices.

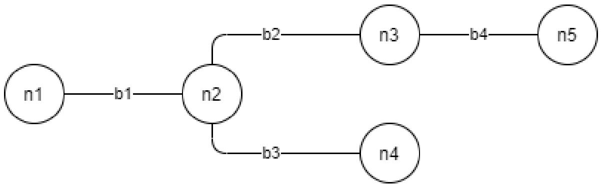

Fig. 3. Topology of a simplified 5-node air distribution network

When the pressures of all nodes are specified, as listed in Table I, while the flow rates in all branches are unknown, the resistance cannot be uniquely identified. The calculation will be converged at various conditions depending on the initial input of S, which renders the solution infinite. Fig. 4 shows one of the solutions when the initial S of each branch is set to 1. The calculation converges after about 15 iterations. However, changing the initial input of S to different values gives rise to different versions of outcomes (Fig. 5). Even if the initial input of S_{b1} remains unchanged, the converged result differs, which makes the solution ambiguous and unpredictable.

TABLE I. Flow Rate In Each Branch

Branch #	**b1**	**b2**	**b3**	**b4**
Flow rate (m^3/h)	13.85	10.20	3.65	10.20

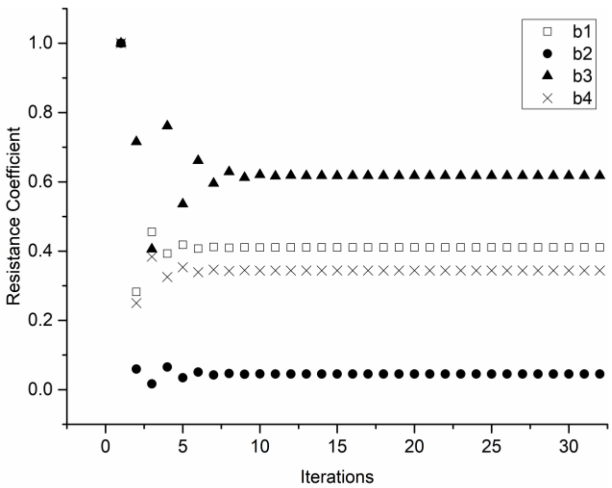

Fig. 4. Simulation results when all flow rates are given and the initial $S_{b1} = S_{b2} = S_{b3} = S_{b4} = 1$

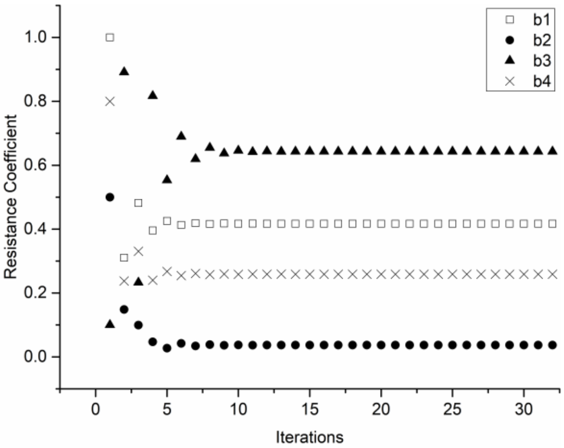

Fig. 5. Simulation results when all flow rates are given and the initial S_{b1} = 1, S_{b2} = 0.5, S_{b3} = 0.1, S_{b4} = 0.8

Similarly, knowing all of the flow rates, as listed in Table II, but none of the pressures also yields indefinite solutions. The results vary according to the initial input of *S*. Fig. 6 and Fig. 7 present two of the solutions with different initial settings. The calculation converges after about 10 iterations, but the results reach no agreement with each other.

TABLE II. PRESSURE AT EACH NODE

Node #	n1	n2	n3	n4	n5
Pressure (Pa)	100	4.03	-79.17	0	-100

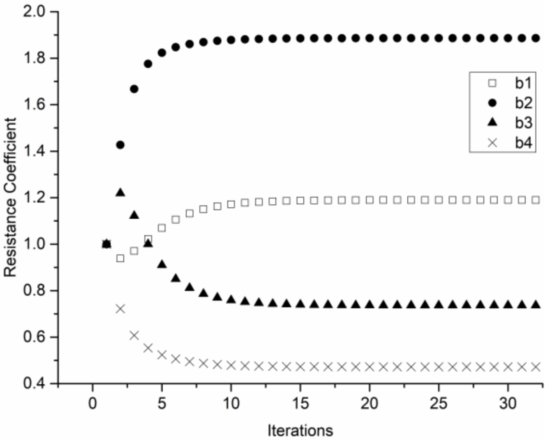

Fig. 6. Simulation results when all pressures are given and the initial S_{b1} = S_{b2} = S_{b3} = S_{b4} = 1

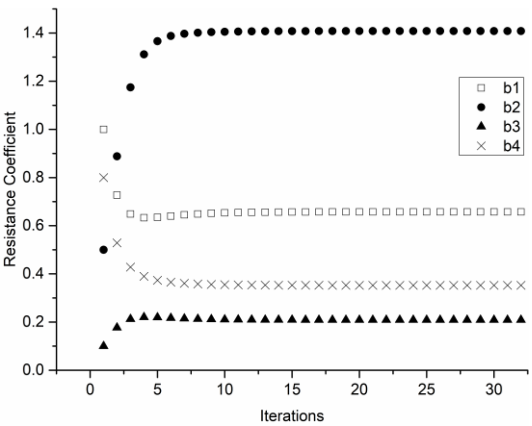

Fig. 7. Simulation results when all pressures are given and the initial S_{b1} = 1, S_{b2} = 0.5, S_{b3} = 0.1, S_{b4} = 0.8

More constraint conditions shall be applied to achieve a unique solution. It is observed that even when all the flow rates are provided, the resistance cannot be uniquely determined unless all the pressures are given. This is because equation (1) is no longer constrain when all the flow rates are known, and equation (2) itself is not able to provide sufficient constraints since both *P* and *S* are independent variables. Therefore, we can primarily conclude that one of the necessary conditions to uniquely identify *S* is that the pressure at all nodes shall be prescribed.

Furthermore, the flow rate in the branches shall be selectively specified so that the unknown flow rates can be inferred or deduced from the known ones via equation (1). Otherwise, equation (2) is not able to provide sufficient constraints because both *Q* and *S* are independent variables. In the current case study, at least two flow rates among the branches of b1, b2 (or b4), and b3 shall be provided to ensure that all the flow rates across the network can be uniquely secured.

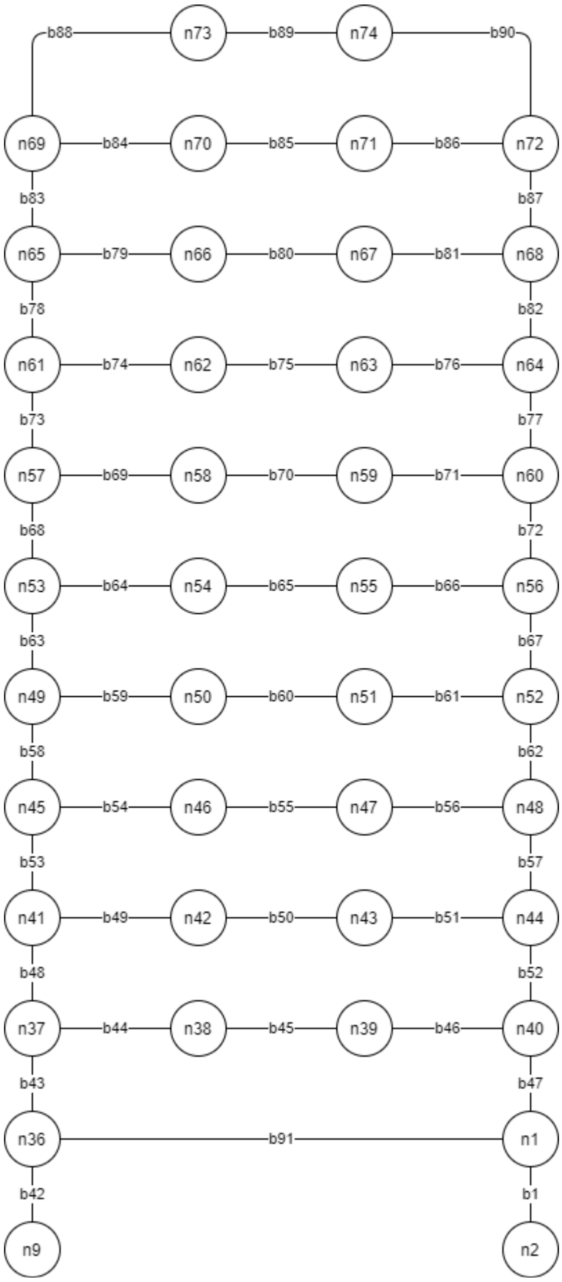

Fig. 8. Topology of a typical 42-node water circulation network

By applying these two constraint conditions to the study case, the resistance is no longer dependent on the initial input of S and thus can be uniquely identified. No matter what initial values are assigned to S, the calculations converge to identical results, as presented in Fig. 8 and Fig. 9. Table III lists the final solution.

TABLE III. RESISTANCE RESULTS

Branch #	b1	b2	b3	b4
Resistance Coefficient	0.5	0.8	0.3	0.2

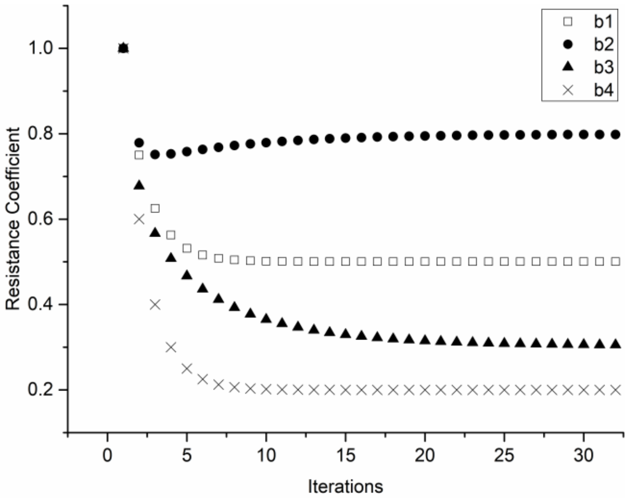

Fig. 9. Simulation results with sufficient constraints and the initial $S_{b1} = S_{b2} = S_{b3} = S_{b4} = 1$

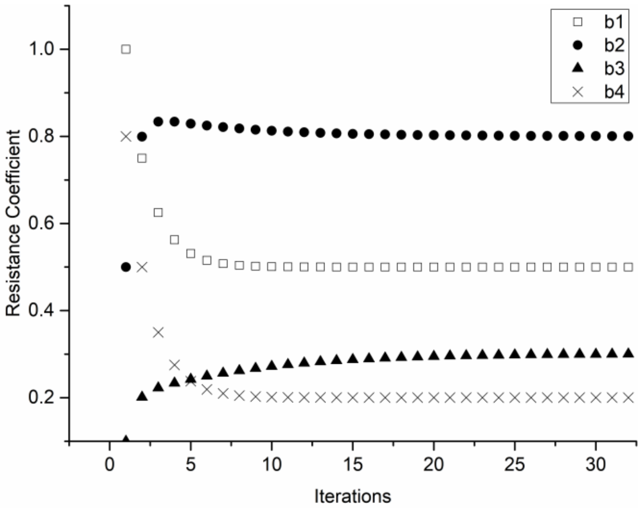

Fig. 10. Simulation results with sufficient constraints and the initial $S_{b1} = 1$, $S_{b2} = 0.5$, $S_{b3} = 0.1$, $S_{b4} = 0.8$

The algorithm is further implemented on a more complicated water circulation network as shown in Fig. 10. The topology includes 42 nodes and 51 branches. Based on the conclusions previously achieved, the pressures at all the nodes (Table IV) and the flow rates in the selective branches (Table V) shall be prescribed. The branches are selected by making sure that all the unknown flow rates can be inferred from the known ones. Otherwise, the iterations will be converged to some other unexpected results. In this case, the branches on the right border of the network are chosen because as long as the flow rates in these branches are specified, the flow rates in other branches can be figured out by equation (1). That is to say, a network structure analysis shall be performed to select the necessary branches.

TABLE IV. RESISTANCE RESULTS

Branch #	Resistance Coefficient	Error	Branch #	Resistance Coefficient	Error
b1	6.50	0%	b67	59.44	-1%
b42	6.46	-1%	b68	81.63	-6%
b43	65.43	-9%	b69	8229.54	-5%
b44	8467.89	-2%	b70	137536.56	-4%
b45	141034.45	-2%	b71	32968.81	-5%
b46	55075.11	-2%	b72	86.40	0%
b47	71.86	0%	b73	127.31	-6%
b48	24.35	-9%	b74	8280.95	-4%
b49	8138.58	-6%	b75	137920.65	-4%
b50	135888.07	-6%	b76	28996.96	-4%
b51	48905.27	-6%	b77	133.63	-1%
b52	26.70	0%	b78	232.73	-3%
b53	30.70	-9%	b79	8333.24	-4%
b54	8112.70	-6%	b80	139313.51	-3%
b55	135118.62	-6%	b81	25085.26	-3%
b56	44595.66	-6%	b82	240.00	0%
b57	33.53	-1%	b83	524.73	-3%
b58	40.82	-7%	b84	8450.36	-2%
b59	8130.41	-6%	b85	140742.17	-2%
b60	135820.49	-6%	b86	21126.91	-2%
b61	40789.26	-6%	b87	534.20	-1%
b62	44.10	0%	b88	10798.88	0%
b63	55.38	-8%	b89	143859.19	0%
b64	8174.88	-5%	b90	19440.00	0%
b65	136154.19	-5%	b91	13.00	0%
b66	36745.04	-5%			

TABLE V. PRESSURE AT EACH NODE

Node #	n1	n2	n9	n36	n37	n38	n39
Pressure (Pa)	73.08	100.00	0.00	26.74	28.15	29.95	59.85
Node #	n40	n41	n42	n43	n44	n45	n46
Pressure (Pa)	71.52	28.58	30.37	60.29	71.05	29.01	30.80
Node #	n47	n48	n49	n50	n51	n52	n53
Pressure (Pa)	60.72	70.59	29.44	31.23	61.14	70.12	29.87
Node #	n54	n55	n56	n57	n58	n59	n60
Pressure (Pa)	31.66	61.59	69.66	30.30	32.09	62.03	69.20
Node #	n61	n62	n63	n64	n65	n66	n67
Pressure (Pa)	30.74	32.53	62.46	68.75	31.18	32.97	62.90
Node #	n68	n69	n70	n71	n72	n73	n74
Pressure (Pa)	68.29	31.62	33.42	63.35	67.84	33.87	63.80

However, it is noticed that the network forms a closed loop. According to the Kirchhoff's first law, the flow rates in the branches of b1 and b42 can be inferred from each other since the sum of flow flowing into the loop is equal to the sum of flow flowing out of the loop. The Kirchhoff's second law also provides clues to deduce the pressures as the directed sum of the pressure differences around any closed loop is zero, i.e., the pressure of node n40 can be determined from pressures of nodes n1, n36, n37, n38, and n39. Therefore, Kirchhoff's laws can theoretically help reduce the number of known conditions for the closed-loop network. However, due to the decentralized structure of the CIS, none of the nodes has the overall information about the network. Through exchanging information with its neighbors, a node is incapable to detect whether the network is a closed loop, what nodes are in the loop, or how the loop is structured. Thus, without further development or manual configurations, Kirchhoff's laws regarding the closed-loop topology tend to be unhandy to execute via the current calculation algorithm.

With all the initial inputs indicated above and after hundreds of iterations, all the unknown resistances were successfully found (Table VI). The maximum error is about 9%. Fig. 11 shows the convergent tendency of the resistance calculation for sample branches. Due to the large number of nodes and the complexity of the network, the simulation took a longer time to converge and did not reach a desirable result until about 400 iterations.

TABLE VI. FLOW RATE IN SELECTED BRANCHES

Branch #	**b1**	**b47**	**b52**	**b57**	**b62**	**b67**
Flow rate (kg/h)	2.035	0.147	0.133	0.118	0.103	0.088
Branch #	**b72**	**b77**	**b82**	**b87**	**b90**	
Flow rate (kg/h)	0.073	0.058	0.044	0.029	0.014	

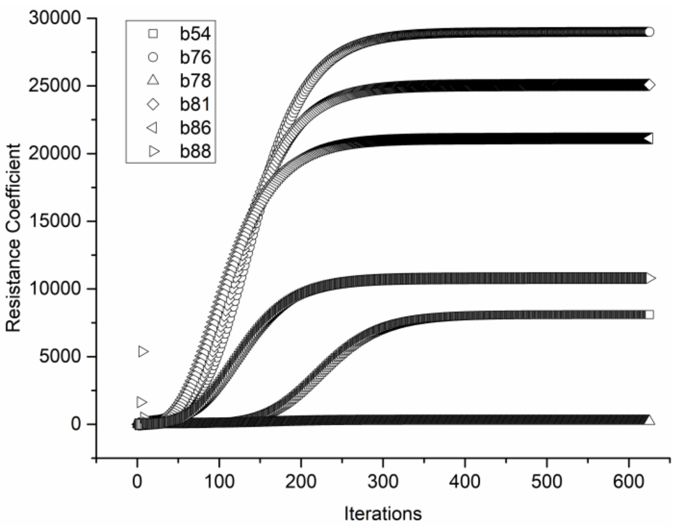

Fig. 11. Convergent profile of resistance calculation

The proposed method with the CIS concept is thereby proved to be able to identify resistance for HVAC distribution networks. It thus can be exploited to assist fault diagnosis in practical engineering such as leakage or blockage detection. By calculating the resistance of the branches and recognizing the abnormal values, the leaking or blocked branches can be located. For complex distribution networks, a particular section can be zoomed in and analyzed individually upon actual demands, as long as sufficient constraints are applied. For instance, each loop in Fig. 10 can be independently studied with its own boundary conditions.

IV. CONCLUSIONS

This paper implemented a novel CIS concept for resistance identification in the HVAC distribution network. The identification principle and algorithm were described and examined by its application on a simple air distribution network and a typical water circulation system. The following conclusions are mainly achieved.

By solving the basic energy and flow balance functions and exchanging information between neighboring nodes, the system can achieve a global convergence with the proposed approach. However, without sufficient constraints, the solution is indefinite and unpredictable.

The necessary conditions to secure a unique solution was investigated. For an open-loop topology, all pressures and necessary flow rates shall be prescribed. For a closed-loop system, additional constraint conditions are available according to Kirchhoff's laws but may require further development to fulfill.

The proposed method has the potential for fault diagnosis by identifying the resistance of the branches and locate the abnormal values.

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REFERENCES

[1] J. C. Lam, "Energy analysis of commercial buildings in subtropical climates," Building and Environment, vol. 35, no. 1, pp. 19-26, 2000.

[2] H. Wang, W. Zhou, and H. Zhou, "Analysis on pipe network resistance parameter calibration approach in district heat supply," Chinese Journal of Computational Physics, vol. 30, no. 3, pp. 422-432, 2013.

[3] L. E. Ormsbee and D. J. Wood, "Explicit pipe network calibration," Journal of Water Resources Planning and Management, vol. 112, no. 2, pp. 166-182, 1986.

[4] K. E. Lansey and C. Basnet, "Parameter estimation for water distribution networks," Journal of Water Resources Planning and Management, vol. 117, no. 1, pp. 126-144, 1991.

[5] M. Greco and G. D. Giudice, "New approach to water distribution network calibration," Journal of Hydraulic Engineering, vol. 125, no. 8, pp. 849-825, 1999.

[6] J. Vitkovsky, A. Simpson, and M. Lambert, "Leak detection and calibration using transient and genetic algorithms," Journal of Water Resource Planning and Management, vol. 126, no. 4, pp. 262-265, 2000.

[7] Y. Liu, P. Zou, Z. Zhou, C. Lei, and P. Wang, "Identification method of resistance characteristic coefficient in heat-supply networks based on minimal norm solution of equations," Heating Ventilating and Air Conditioning, vol. 41, no. 2, pp. 80-84, 2011.

[8] D. A. Savic and G. A. Walters, "Genetic algorithm techniques for calibration network models," Report No 95/12, Centre for Systems and Control Engineering, University of Exeter, Devon, 1995.

[9] Z. Zhou, P. Zou, H. Tan, and J. Wang, "Identification of resistance coefficient for heat-supply network based on GASCAA algorithm," Journal of Harbin Institute of Technology, vol. 40, no. 11, pp. 1761-1765, 2008.

[10] X. Qin and Y. Jiang, "Identification of flow resistance coefficient and fault diagnosis in district heating networks," Journal of Tsinghua University (Science and Technology), vol. 40, no. 2, pp. 81-85, 2000.

[11] Z. Yu and H. Li, "Identification of flowrates and pressures in HVAC distribution network based on collective intelligence system," in Proceedings of the 11th International Conference on Modelling, Identification and Control (ICMIC2019), pp.1229-1237, Tianjin, 2020.

[12] Z. Yu, H. Li, and W. Liu, "Topology description of HVAC systems for the automatic integration of a control system based on a collective intelligence system," in Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019), pp.883-891, Harbin, 2019.