Fully automated controller for the real-flow calibration of natural gas flowmeters based on hybrid driven model

X. Han[1],H.W. Zheng[1], C.F. Song[1],L Zhou[1], Y. Wu[1], B.Y. Hong[2],K. Wen[3*]

[1]Nanjing Metrology Research Center, PipeChina West East Gas Pipeline Company, China
[2]Zhejiang Ocean University, Zhoushan，China
[3]China University of Petroleum-Beijing, Beijing, China
E-mail (corresponding author): kewin1983@126.com

Abstract

With the rapid development of the natural gas industry, the natural gas measurement handover volume is increasing year by year, and the calibration of natural gas flowmeter is becoming more and more important. This paper defines and demonstrates the framework of a fully automated controller for natural gas flowmeter calibration stations, from conceptualization to field test. When the calibrated flowmeter is installed on bench, the controller will identify the corresponding process by success tree algorithm. It checks whether the current process is appropriate, and automatically switch the best process according to the diameter of the calibrated meter. In the regulation stage of different calibrated flow rates, the controller performs predictive control on different flow rates according to the actual hydraulic condition by the calculation of hybrid driven model based on neural network model and mechanism model. This process gives the initial position of regulating valves with fast and efficient movement. Under a mild PID control law, the actual flow will go to the setting flow rates neither overshoot nor fall back. Finally, the control scheme is demonstrated in three original case studies, one in the simulation environment built by hydraulic simulation software, and the other two in real systems with different complexity. The algorithm is verified by simulation software and the control scheme is implemented in the actual environment. The results show that the intelligent calibration process based on model predictive control can increase the calibration efficiency. The integrated system based on hybrid driven can promote the intelligent development of natural gas calibration stations.

1. Introduction

Artificial Intelligence (AI) is changing our world in an all-round way and is gradually becoming a new way of research. In July 2020, an interesting article was reported on the cover of Nature that scientists from the University of Liverpool had developed an ‘intelligent scientific robot’, which can decide what experiments to do, and can work seven days a week without weekends. Similar to chemical experiments, the real-flow calibration of natural gas flowmeters also requires a large number of the operations by professionals. For a typical gas flow meter calibration station, there are 12 sections in the real-flow calibration station and hundreds of equipment and valves work accordingly to make the flow through the test flowmeter meet the error requirements. Meanwhile, the parameters adjusted range from 8 to10000 m^3/h and from 4 to 10 MPa. Therefore, the fast and precise regulation of equipment and valves is the daily work of the experienced operators. At the same time, the real flow calibration is adopted in China by cutting off the mainline gas source, so that the natural gas enters the natural gas flowmeter calibration station and thus the calibrated flowmeter is calibrated. The flowmeter online real flow calibration takes full account of the physical parameters of the natural gas, the operation of the flowmeter, installation factors and environmental factors and other conditions, so that the flowmeter calibration conditions are consistent with the actual conditions of use as far as possible. This method is the most consistent with the flow traceability characteristics of the calibration method [1]. In the flowmeter calibration process, the full process of a calibrated flowmeter takes about 3 hours, mainly including process conduction and flow adjustment operations, the most time-consuming part of which is the flow adjustment of the calibration flow point. Due to the complex pipelines in the station, the frequent switching of processes and the large changes in the calibration conditions, and the valve adjustment of the regulating valve is affected by the transient changes in the hydraulic system of the station, making the rapid adjustment of the flow point one of the core difficulties of the calibration operation. However, the rapid adjustment of flow point is extremely dependent on the professional level of the verifier, which restricts the flowmeter checking ability of the calibration station [2]. Traditional schedulers based on human experience cannot meet these challenges because they cannot provide solutions tailored to the actual situation.

For the whole calibration system, it must become intelligent, optimal, sustainable and interconnected. Han [2] discussed the feasibility of intelligent calibration management system and calibration control system of flowmeter calibration system in 2018. In 2020, Liu et.al [3] explored the intelligent research of natural gas metrology calibration, and established an intelligent route taking the data passing and sharing metrology calibration data as the center, the digital twin as the simulation model, the big data drive mode as the carrier and the image recognition VR technology as the supervision. In 2021, Zheng et.al [4] explored and prospected the intelligent technology of natural gas measurement and calibration. The applications of Internet of things and intelligent algorithm, measurement standard integrity technology, measurement big data technology and intelligent storage intelligent disassembly technology in natural gas flowmeter calibration station are pointed out. In the application level, Wen et.al [5] carried out the hydraulic modeling of Guangzhou natural gas flowmeter calibration station through HYSYS, combined with control theory to completely demonstrated the whole process using program control method. On the basis of Wen Kai, Han et.al [6] used the hydraulic simulation model SPS to model the Guangzhou natural gas flowmeter calibration station, and put forward the optimal operation scheme for the field valve adjustment according to the simulation results. Wu et.al [7] carried out the intellectualization the calibration process of natural gas flowmeter, and investigated the quality control of the calibration process of natural gas flowmeter using multiple regression linear prediction test data calibration of historical data. Wen et.al [8] modeled the calibration station of natural gas flowmeter through neural network, and generated the control scheme through neural network. In January 2022, Yin et.al [9] used the agent model based on machine learning to model the flow control of pipeline, and simulated the application in the calibration system of natural gas flowmeter. However, at present, it is difficult to find the research work that covers all the steps of modeling, testing, development and field application of the whole intelligent calibration system, or to put forward a general platform for the whole process intelligent control of different calibration stations. There is still a lack of effective and fast full-process automatic control method for natural gas flowmeter calibration station.

The mechanism model comes from the control of the hydraulic system and the whole control scheme is standardized. In addition, a large number of production data are retained with the tide of intelligent pipeline and intelligent pipe network, which provides the basis for the training of the data model, so a control model based on data coupling can be proposed. Therefore, the coupling mechanism and the control model of data are intelligent to realize the whole flow control of the natural gas flowmeter calibration station for the following reasons:

1. It predicts the external conditions and the behavior of the system accurately, allowing for unexpected changes and phenomena in the slowly varying parameters of the system.
2. It calculates the optimal control action through the optimization algorithm. For a multi-input and multi-output system, the automatic operation of the whole control flow and the digitalization can be realized.
3. It makes full use of the flowmeter calibration data and station operation data retained during the operation of the natural gas flowmeter calibration station, and constructs the success tree of the natural gas flowmeter calibration station according to the identification of the key valve switch. the flow of the natural gas flowmeter calibration station can be identified according to the current working conditions, and a more reasonable valve opening scheme is given, which plays a positive role in the on-site valve control.
4. It has a test platform for simulation control algorithm, which can test and effectively verify the control algorithm before implementation, which ensures the reasonable closed loop of the control algorithm.

Based on the above advantages, this paper proposes fully automated controller for the real-flow calibration of natural gas flowmeters based on hybrid driven. The prototype system is used to effectively control the process equipment of two national oil and gas large flowmeter calibration station of Guangzhou sub-station and Nanjing sub-station. These experimental case studies are field tests of different complexity, which prove that the technical level of the controller has reached the closed loop and can be applied in the field.

2. Design of intelligent control system for flowmeter calibration

As shown in Figure 1, a simulation platform for natural gas flowmeter calibration was first established using the hydraulic simulation software SPS based on the topology of the actual natural gas flowmeter calibration station on site and the pipeline information ledger. The established platform was then calibrated according to the field production data. The calibrated platform is used to simulate operations that are not involved in field production during the testing phase and is used to generate better control strategies. In fact, the established SPS simulation platform is not only a control algorithm test platform, but also a simulation platform. After calibrating the platform, the platform can be simulated in the face of the operating conditions not involved in the field, so as to effectively supplement the field data. Then, through the identification of the key valves affecting the flow in the whole production process through the production data, a success tree is constructed to identify the on-site workflow, and the flow is initially adjusted by the neural network. At the same time, the input of the mechanism model is predicted according to the neural network, and the flow is further adjusted by the mechanism algorithm, so as to couple the mechanism model with the data model. The whole calibration process is automatically controlled by the theory of model predictive control (MPC).

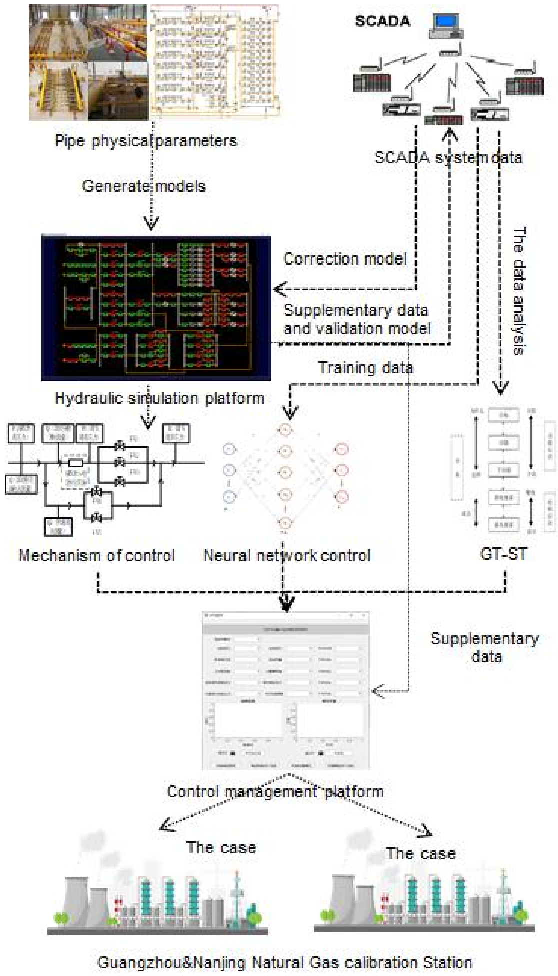


Figure 1: The whole process control system of natural gas flowmeter calibration station

2.1 Construction of test platform for control scheme

Field testing of the new control strategies is not always feasible due to compliance with service requirements, technical problems or economic feasibility. Therefore, mathematical modeling of field equipment simulation is a good choice because it allows the implementation, testing and improvement of control strategies, and may significantly save time and money. For this reason, the author has established a 1:1 platform consistent with the field in the SPS environment. SPS has been proved to be a reliable tool for oil and gas pipeline simulation, which is suitable for testing and evaluating the new control strategy without affecting the actual system. The calculation of the pipe segment is described by continuity equation, motion equation and energy equation.

For the regulating valve, there are different calculation formulas considering the compressibility of gas. When it is a non-blocking flow ($\Delta \mathrm{p} < 0.5 C_f^2 P_u$), the formula for calculating the gas control valve is

$$Q = C_v N \sqrt{\left(p_u^2 - p_d^2\right)/\left(ZGT\right)} \qquad (1)$$

where Q the volume flow in the standard state, m^3/h ; Z the compression coefficient under the upstream temperature and average pressure, G the specific gravity of natural gas relative to the air, T the upstream temperature, K ; P_u the inlet pressure, P_d the outlet pressure, Pa ; C_f the critical flow coefficient, the value is 1; the unit conversion coefficient is 0.0346. C_v is the flow coefficient of the valve.

2.2 Calibration process identification based on GT-ST method

During the routine operation of the calibration station, the station meets the process requirements of flowmeter calibration by adjusting the working status of the process system, such as inlet and outlet pipeline, cross-station bypass pipeline, filter separation device, pressure regulation device, calibration level standard device, working level standard device, primary standard device, secondary standard device, calibration station, flow regulating valve group, back pressure valve group, pressurization device and so on. The working status of each device plays an important role in the operation of the calibration station, and the working state determines the process of the complex system of the calibration station.

The Goal Tree-Success Tree (GT-ST) method is a functional decomposition framework for complex systems. This method interprets the establishment process of the system as a hierarchical development process [10], decomposes the basic elements of the complex system, and presents its hierarchical structure in the form of a tree to show the relationship between functions and elements.

As shown in the figure 2, GT-ST is a hierarchical structure of complex system functions, which takes the goal as the starting point and clearly describes the main purpose of the system (or the main purpose that needs to be achieved). In this method, the overall goal is divided into necessary and effective sub-goals, in other words, the functions needed to achieve the overall goal, and the sub-goals have their corresponding sub-functions. The construction of GT is realized through the decomposition process, for example the process identification in the calibration station is divided into cross-station process, conventional calibration process, accident process and other processes. For the sub-function, the realization of each function requires the function of one or more system elements, decompose the system into a single element, through the combination of elements to achieve sub-functions, then achieve the construction of ST.

Through the GT-ST method, the elements, objectives, actions and other factors of a complex system can be organically combined, the process of calibration station can be rationally decomposed, and the process of calibration station can be obtained according to the state combination of the basic elements. At the same time, each function after decomposition is coded according to the combination process of the basic elements, and the standardized data description of the station state is realized.

The construction process of GT-ST model is essentially a combination process of "goal", "sub-goal" (function), "sub-function" and "basic element" system element "sub-function". It can be divided into three steps [11]:

(1) Determining the general goal and basic elements of the system. According to the research purpose, the general goal of the system is determined. In the establishment of the conventional GT-ST model, the basic elements should be decomposed at the end, but for the process identification of the calibration station, the basic elements (equipment status and natural gas flow characteristics) are relatively simple, so they are determined in the first step.

(2) Decomposing the target. According to the research purpose and the actual system structure, the overall goal is decomposed into sub-goal and the sub-goal is decomposed into functions.

(3) Merging of basic elements. The accurate description of each sub-goal is realized through the combination of the existing basic elements or the combination of the basic elements.

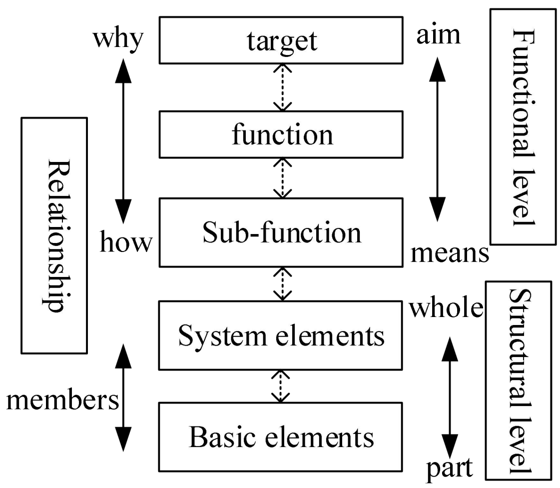


Figure 2: GT-ST hierarchical structure

2.3 Design of flow controller based on MPC

Mechanism model is the accurate mathematical model established according to the object, the internal mechanism of the production process, or the transfer mechanism of material flow. It is a mathematical model of an object or process based on mass balance equation, energy balance equation, momentum balance equation, phase balance equation, some physical property equations, chemical reaction laws, basic laws of circuit and so on. The advantage of the mechanism model is that the parameters have a very clear physical meaning. The reasonable mechanism modeling of the controlled object is carried out, and through the operating conditions and reasonable modeling simplification, a reasonable and adaptive control strategy can be output to the controlled object. However, for the nonlinear time-delay system, the flow control of the gas flowmeter calibration station involves a wide range of control conditions, and there are many types of process switching. Therefore, for the control of this kind of system, only from a modeling and control scheme, it is not consistent with the actual working conditions on the spot. Therefore, under the control scheme established by the mechanism model, the neural network modeling is used as a supplement to control the flow of the gas flowmeter calibration station.

For the mechanism model, by assuming that the pressure of the inbound and outbound stations flowing through the natural gas flowmeter calibration station remains unchanged, the flow distribution under the current total operating conditions is realized by adjusting the opening of the flow regulating valve and the bypass valve. Therefore, the following simplified model control system is designed.

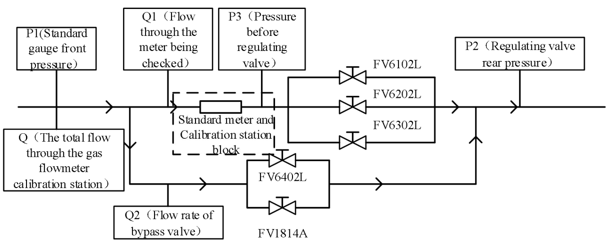


Figure 3: Mechanism model control system

As shown in the figure 3, the mechanism model control system constructed by the simplified model of the natural gas flowmeter calibration station focuses on the action of the control valve concerned in the calibration process. The control system is an open-loop control, and the specific implementation steps are as follows:

Step1. When the pressure difference is small and the total flow is constant, it can be assumed that the pressure in and out of the station remains the same and the total flow remains the same. That is, P1, P2 and Q are fixed values.

Step2. The flow at the bypass is calculated by bypassing the current opening. The verified flow of the standard flow meter and the calibrated flowmeter can be read directly, and then the total flow Q can be calculated through the sum of the current bypass flow and the regulated flow.

Step3. Identify the friction of the process. Under each process, the friction coefficient used to calculate pressure drop between the standard meter and the calibrated flowmeter is used as a backup for the database. If there is no historical data, the current steady state value can be used to calculate the current friction coefficient.

Step4. According to the calibration process of the target flow, the standard flowmeter and the friction coefficient of the calibration table is selected. Through the target flow, P1 and the friction under the calibration process, the pressure P3 in front of the valve is obtained when adjusting to the set value of the calibration flow.

Step5. According to the principle of opening the valve with large diameter first, the opening of the large diameter regulating valve is calculated by the pressure before and after the regulating valve, the target flow rate and the flow coefficient of the valve. Considering the openability of the actual valve, the calculated opening is rounded. For the flow that can not be adjusted, the valve adjustment algorithm will continue to use the valve formula to calculate the opening of the small diameter valve. And so on, the opening of each regulating valve can be calculated.

Step6.For the flow through the bypass valve, the bypass flow is obtained by subtracting the target flow from the total flow.

Step7. Similarly, according to the principle of opening the large diameter control valve first, the opening of the large diameter control valve is calculated and rounded. Then use the small caliber control valve for the next step of adjustment.

For the equal percentage valve, under a certain pressure difference, the required opening through a certain flow is calculated by formula 2.

$$x = \ln\left(1 + \frac{\left(e^{3.488} - 1\right)Q}{C_{vo}N\sqrt{\left(p_u^2 - p_d^2\right)/\left(ZGT\right)}}\right) \Big/ 3.488 \qquad (2)$$

For linear valves, under a certain pressure difference, the required opening through a certain flow rate is calculated by formula 3.

$$x = \frac{Q}{C_{vo} N \sqrt{\left(p_u^2 - p_d^2\right)/(ZGT)}} \quad (3)$$

The end pressure and friction coefficient of the pipe section are calculated by formula 4 and formula 5.

$$p_Z = \sqrt{p_Q^2 - \frac{\left(Q_p/C_0\right)^2 \lambda Z \Delta_* TL}{D^5}} \quad (4)$$

$$\lambda = C_0^2 \frac{\left(p_Q^2 - p_Z^2\right) D^5}{Q_P Z \Delta_* TL} \quad (5)$$

where Q the volume flow in the standard state, m^3/h ; Z the compression coefficient under the upstream temperature and average pressure, G the specific gravity of natural gas relative to the air, T the upstream temperature, K ; P_u the inlet pressure, P_d the outlet pressure, Pa ; C_f the critical flow coefficient, the value is 1; the unit conversion coefficient is 0.0346. C_v is the flow coefficient of the valve. x is valve opening of regulating valve.

The input and output of the neural network are set according to the function of the natural gas flowmeter calibration controller. The function is to give the opening of five regulating valves according to the current working condition and target flow. Therefore, the calibration flow, station equipment status and station process parameters are used as inputs of the BP neural network, while the opening of the five valves is used as output to build a control neural network model, as shown in figure 4.

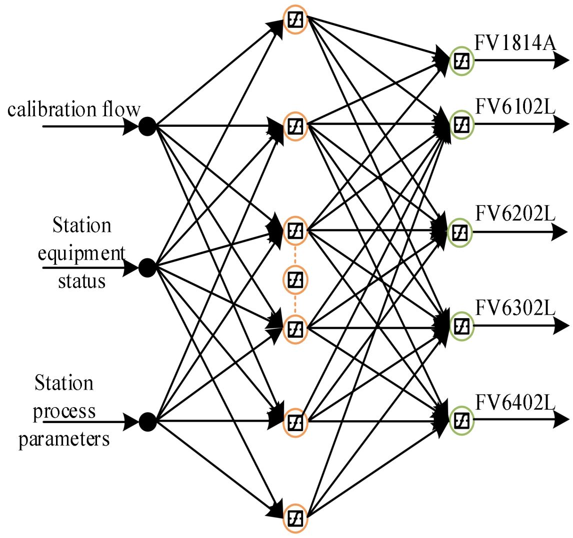


Figure 4: Control neural network model

For the network structure and super-parameters of the neural network, the network structure, weight and threshold of the neural network are optimized by the combination of cross-verification and genetic algorithm to enhance the adaptability of the neural network. The neural network optimization process is shown in figure 5:

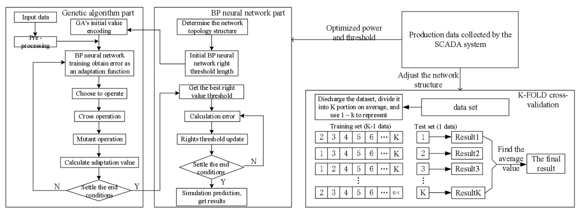


Figure 5. Neural network optimization process

Because the above schemes are open-loop calculation schemes, in order to make the whole scheme closed-loop, the idea of Model Predictive Control (MPC) is adopted to make the whole scheme closed-loop. MPC is a multivariable controller which controls the output simultaneously by considering all factors. With the continuous development of MPC theory, MPC has been applied in petrochemical industry [12-14], HVAC [15], autopilot [16], sewage treatment [17] and other fields. The developed algorithm uses multi-input and multi-output MPC, coupled GT-ST process identification, mechanism model and neural network model. The whole process control process is shown in figure 6. First of all, the process of the calibration station is identified by GT-ST, and the appropriate standard flow meter and calibration branch are checked and switched automatically. After switching to the calibration process, the initial adjustment is carried out through the BP neural network, and then the model predictive control regulation of the flow is carried out according to the combination of the BP neural network and the mechanism model to make the calibration flow reach the target calibration flow point. These processes are then repeated until all target flow points are calibrated. Through this process, the whole process automatic control of the calibration production task of the calibration station is achieved.

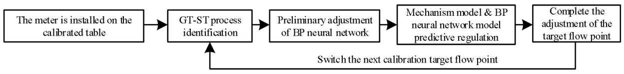


Figure 6: Whole process control process

3. Case study

In order to verify the closed-loop property of the control algorithm, the SPS simulation platform is used as a tool to develop, evaluate and compare new control strategies in complex systems that have not been designed, debugged or difficult be tested. This paper takes an actual natural gas flowmeter calibration station as an example (figure 7). The flow control system consists of 246 ball valves, 24 regulating valves and 116 high-pressure natural gas pipelines. Among the calibration station, the working standard is the core part of the calibration station, which is generally composed of high-precision turbine flowmeter and ultrasonic flowmeter installed in parallel. The working standard is mainly used to calibrate various types of natural gas flowmeters used in the field. Calibration stations are generally equipped with a set of metrological calibration process system and auxiliary system to verify the production task of the calibrated flow meter, and the common technological process is mainly composed of 11 parts. (1) process flow of natural gas in and out of station; (2) technological process of natural gas filtration and separation; (3) technological process of natural gas heating; (4) technological process of natural gas pressure regulation; (5) natural gas temperament measurement process; (6) natural gas flow regulation process; (7) natural gas quantity transfer process; (8) natural gas residual gas recovery process; (9) discharge process, venting process; (10) ESD valve process;(11) the technological process of flowmeter verification station.

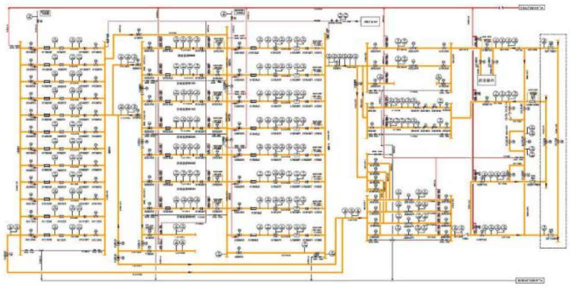


Figure 7. One natural gas flow measurement test station P&ID diagram

3.1 Construction and calibration of test platform

The quantity concerned by the calibration station is the calibration flow and the cross-station pressure drop. Therefore, combined with the analysis of the boundary conditions collected at the calibration station, the hydraulic simulation model is set to the boundary conditions of constant pressure at both ends. Through the interaction with the field station control system, the information of the calibrated flow meter, the selection of the standard flow meter, the opening of the control valve, the switch of the cut-off valve and the pressure extraction of the boundary are input to the SPS software. Then the calibration flow and the pressure in the middle of the calibration station are output by SPS software. The data output by SPS simulation is compared with the data collected by the actual SCADA system, which is used to verify the accuracy of the simulation platform.

Figure 8: Natural gas flow measurement station simulation platform

The SCADA system continuously collects the information of 454 instruments and control points in the field with a sampling interval of 2 seconds, obtaining 6864480 group actual operation data of the calibration station. Through the hydraulic simulation software SPS, the accuracy of the platform is verified according to the deviation between the simulated flow and the actual flow.

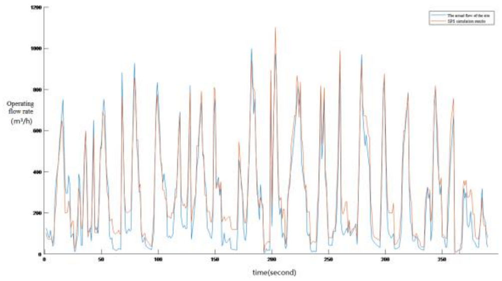


Figure 9: Simulation of natural gas intake condition of branch pipeline

Because of the large pressure drop in the regional process, directly replacing the collected data into the SPS software is easy to cause instability in the SPS software simulation. To avoid this situation, first of all, the steady-state data points are selected to make a good simulation of the intake conditions of the branch line. Then, the accuracy of the hydraulic simulation platform is evaluated through the simulation of steady-state data. Similarly, the pressure in and out of the calibration station is taken as the boundary condition of the SPS software, which is substituted into the platform for simulation. The accuracy of the platform is judged by comparing the calibration flow obtained by on-site and SPS software simulation. As shown in figure 9, for the hydraulic platform under the regional flow, the simulation results at the steady point are basically consistent with the field data, which can meet the simulation of the steady-state working conditions of the regional process and the practical application in the field.

3.2 Verification of process recognition algorithm

The flow identification of the calibration station is carried out according to the tree-building steps, and the overall goal is divided into four sub-targets to build the target tree, and the overall situation of the GT-ST is as shown in figure 10:

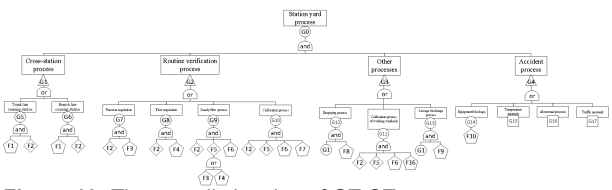


Figure 10: The overall situation of GT-ST

The above steps complete the decomposition of the general goal and sub-goal of GT-ST, which is divided into system elements and basic elements, and the station process is subdivided into 17 groups of processes. Taking F2 as an example, the total conduction of the system elements in the station (F2) is decomposed into basic elements. According to the division of the basic elements of the station, the key valve switches of different devices in the station are taken as the judgment basis, and when each part is connected, it is determined as the conduction of the gas path in the station, and F2 can be divided into four basic elements. The specific decomposition is shown in the figure11:

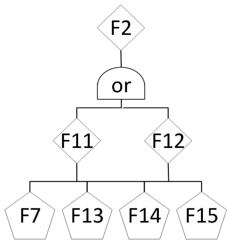


Figure11: Decomposition of total conduction in the station

Table 1: Elements' meanings of GT-ST

Element	Meaning	The main components	The value is 0	The value is 1
F1	Trunk branch situation	Ball valve	Branch line	Trunk line
F2	General in the station	Intersection	Unconducted	Conducted
F3	Pressure regulating valve movement	Regulating valve	No action	Move
F4	Movement valve action	Regulating valve	No action	Move
F5	Each adjustment valve movement	Regulating valve	No action	Move
F6	Stable flow	Intersection	Unstable	Stablize
F7	Inspection site	Ball valve	Unconducted	Conducted
F8	Empty valve action	Ball valve	Unopened	Activated
F9	Sewage valve action	Ball valve	Unopened	Activated
F10	Changes in equipment resistance	Intersection	Unchanged	Change
F11	Large flow pipeline	Intersection	Unconducted	Conducted
F12	Small flow pipeline	Intersection	Unconducted	Conducted
F13	Pressure zone diversion	Ball valve	Unconducted	Conducted
F14	Work standard	Ball valve	Unconducted	Conducted
F15	Direction area	Ball valve	Unconducted	Conducted
F16	Secondary standards	Ball valve	Unconducted	Conducted

The specific meaning of each element in figure 10 is shown in the following Table 1:

The logical relationship between each process and the basic elements is obtained through GT-ST as follows, in which + is an and operation, two events are adjacent to or operation, and it is a non-operation. The identification results of each process can be obtained by operating the Boolean variables in the above table.

$$
\begin{aligned}
G1 &= G5 + G6 \\
G2 &= G7 + G8 + G9 + G10 \\
G3 &= G11 + G12 + G13 \\
G4 &= G14 + G15 + G16 + G17 \\
G5 &= F1\overline{F2}\,\overline{G4} \\
G6 &= \overline{F1}\,\overline{F2}\,\overline{G4} \\
G7 &= F2F3\overline{G4} \\
G8 &= F2F4\overline{G4} \\
G9 &= F2\overline{F5}F6\overline{G4} \\
G10 &= F2\overline{F5}F6F7\overline{G4} \\
G11 &= F2\overline{F5}F6F16\overline{G4} \\
G12 &= G1F8\overline{G4} \\
G13 &= G1F9\overline{G4} \\
G14 &= F10
\end{aligned} \tag{6}
$$

Among them:

$$
\begin{aligned}
F2 &= F7F13F14F15 \\
F5 &= F3 + F4
\end{aligned} \tag{7}
$$

The calibration process of a DN400 flowmeter is consisted of the installation of the instrument, the adjustment process of switching to the designated flow point, the steady flow process waiting for stable working conditions, and the calibration process of flow point calibration. The specific flow changes obtained from data extraction of SCADA are shown as figure 12.

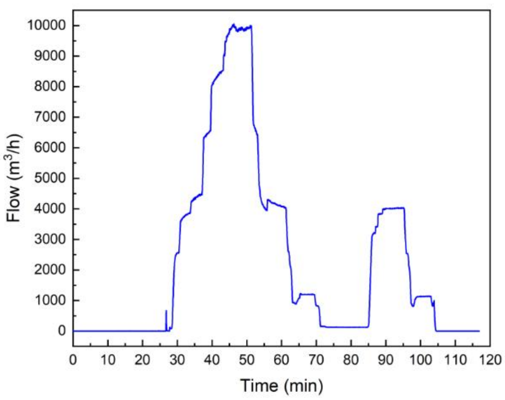


Figure12: Intra-station flow

The process is identified as shown as figure 13. The ordinate is the value identified as 1 in the process identification result at each time point.

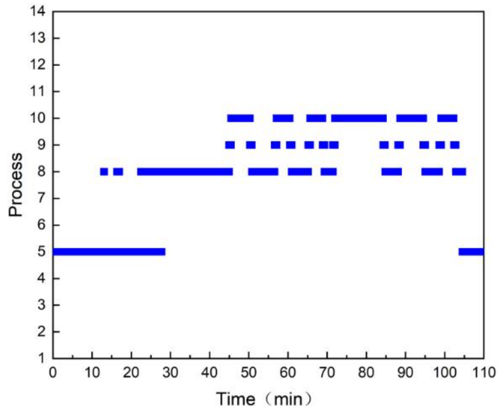
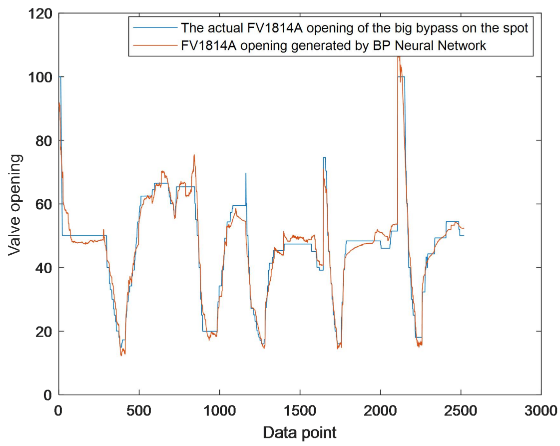


Figure13: Process identification result

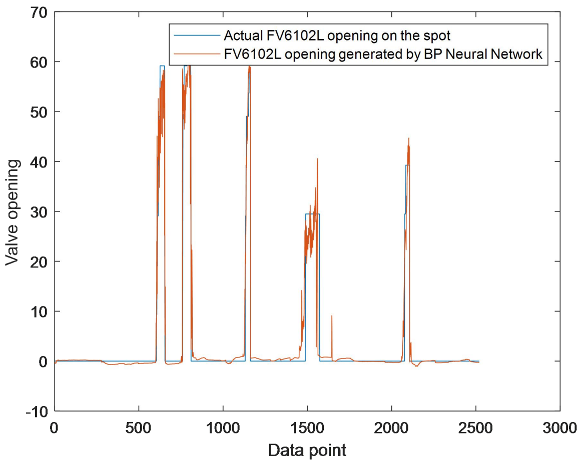
It can be seen that the algorithm can well identify the four processes existing in the calibration station, and standardize the data description of the station state.

3.3 Neural Network Controller Test

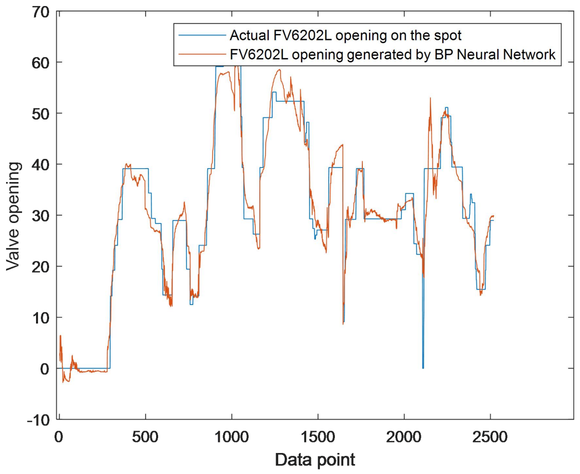
The parameters related to the opening of the flow regulating valve, the calibration flow and the process status of the station are extracted from SCADA system. Among them, 70% of the data is used as training data and 15% is used as verification data, while the remaining 15% is used as test data for BP neural network training. Through cross-verification and genetic algorithm optimization, it is finally determined that the neural network structure is determined as a 10-layer network, including one hidden layer, which takes 1 minute and 19 seconds. 3000 points are evenly selected from the data set to verify the results. As shown in figure 14(a~e), the scheme given by the controller is basically consistent with the actual scheme, which proves the availability of the neural network controller.



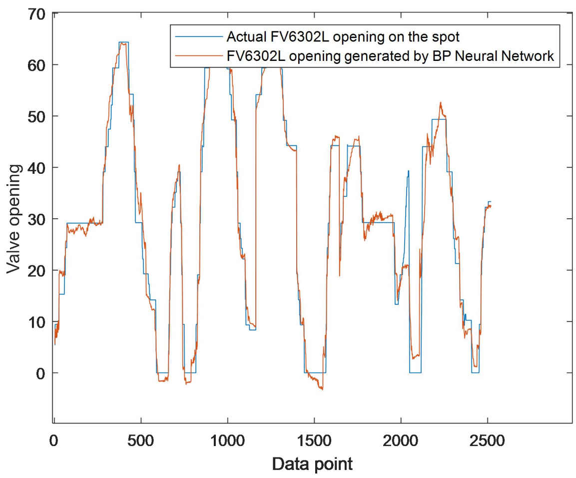
(a)



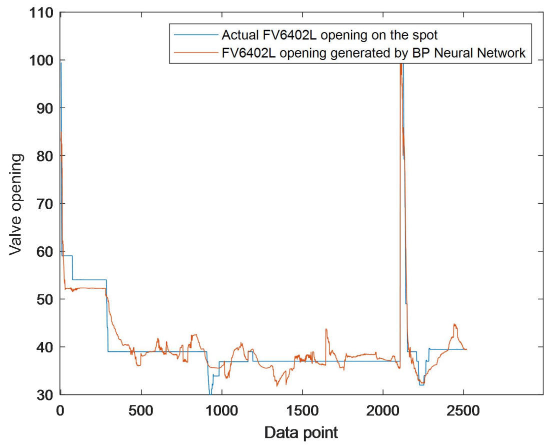
(b)



(c)



(d)



(e)

Figure14: Comparison between controller scheme and actual scheme

3.4 Forecast of front pressure based on BP neural network

In the mechanism control valve model, there is a certain numerical deviation because the position of the measuring instrument in the field is not consistent with that of the hydraulic model. In order to reduce the deviation of the model, the BP neural network is used to predict the front pressure of the regulating valve in this paper. It can be seen from formula 4 that the pressure in front of the regulating valve regulated to the calibrated flow needs to be obtained in advance. Therefore, the pressure in front of the regulating valve can be predicted through neural network, which improves the accuracy of mechanism model calculation.

Neural network has high requirements for data, so it is particularly important to choose the input and output of neural network. Here, the selected inputs are inbound pressure, process, flow, and temperature. The output of the model is the pressure in front of the regulating valve. Through this method, the pressure in front of any flow regulating valve can be predicted. The training results are as figure15:

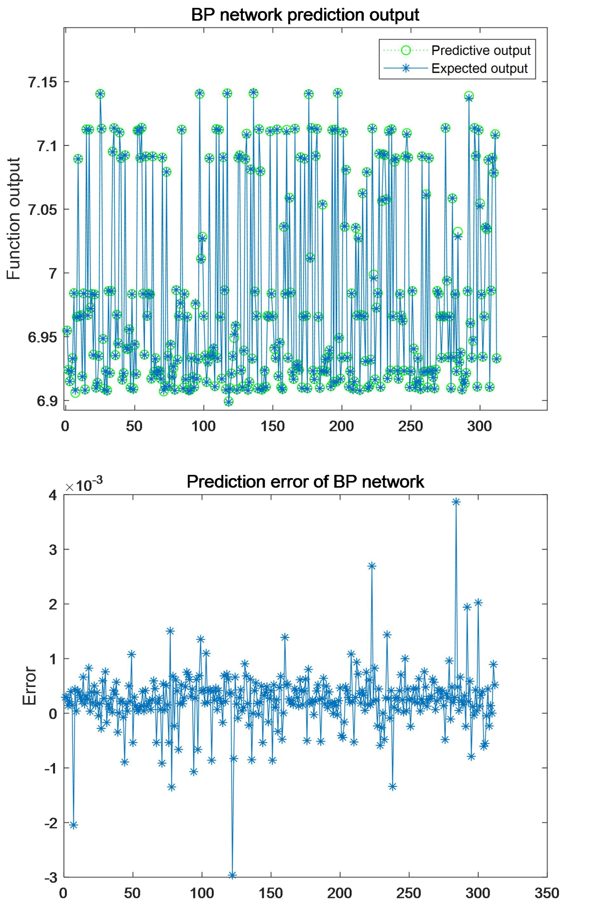


Figure15: Prediction of network output value before regulating valve

As can be seen from the figure 15, after the calibration process is determined, the identification of the pressure in front of the regulating valve has a high degree of fitting. It can provide strong support for the calculation algorithm of valve opening of regulating valve at each verification flow point.

3.5 Model Predictive Control Test

As can be seen from figure 16, during this calibration process, the mechanism model MPC calibration algorithm has been tested for the set calibration flow points of 3200m^3/h, 1500m^3/h and 500m^3/h. Through the mechanism control algorithm MPC adjustment, the open-loop control is closed-loop, and the deviation between the set value and the actual value of the calibration flow point is 3.8%, 2.8% and 0.5%, respectively. It is less than the 5% deviation by the requirements of the National Metrology calibration regulations of the people's Republic of China. It can be seen from the diagram that the predictive control optimization of the mechanism model not only achieves the closed loop of the control effect, but also reduces the number of moving valves and standardizes the regulation of the calibration flow point due to the addition of the concept of valve operation optimization.

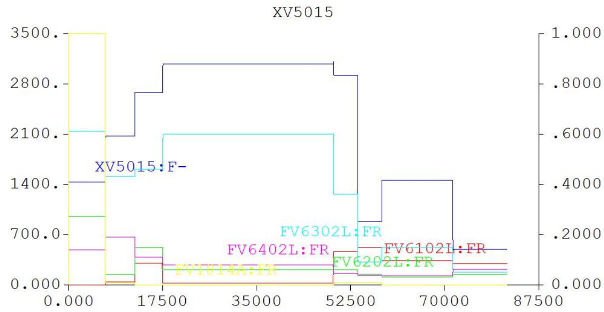


Figure16: Test of Model Predictive Control algorithm

3.6 Field testing

From August 6 to August 14, 2021, the industrial application test of full-process intelligent calibration was carried out in Nanjing Substation, and a total of 11 different caliber flowmeters were calibrated, of which DN400 flowmeter was tested the most and 7 groups of calibration tasks were counted. In the seven calibration processes, there is no operator intervention or program update. The intelligent controller independently identifies the changes of working conditions, and records and optimizes the hydraulic parameters according to the flow points in the calibration process, so that the regulation speed is gradually increased, and the adjustment time is gradually less than 90 minutes. A total of 17 calibration tasks for 11 flowmeters (the verification point is counted as a group of new tasks) are shown in Table 2. The interface of field deployment is shown in Figure 19:

Table 2: Test task table

Test serial number	Caliber	Qmax (min)	0.4Qmax (min)	Qt(min)	Qmin(min)
1	400	29	18	23	17
2	400	/	20	22	/
3	400	28	23	28	27
4	400	/	13	15	/
8	400	16	13	19	14
12	400	22	16	22	20
13	400	/	13	14	/
7	200	24	37	21	25
9	200	33	19	28	13
10	200	/	57	17	/
5	150	27	11	30	/
6	150	/	21	12	/
14	150	28	37	18	19
15	150	/	16	14	/
16	100	26	11	9	12
17	100	22	21	27	14
11	80	29	11	38	11

Figure17: Field software deployment and implementation

The implementation logic of the controller is that when the calibrated flow meter is installed, the calibration controller will take over the whole adjustment process. First of all, the process is identified by GT-ST, and the process of calibration station is adjusted to the calibration process by automatically switching the standard flow meter and flow conduction work according to the target calibration flow point. Then, for the adjustment of each target calibration flow point, it is no longer necessary for the on-site inspector to adjust each calibration flow through frequent mouse clicks, but automatically according to the built-in algorithm of the intelligent controller. Through the industrial application test in Nanjing substation, the results show that the intelligent control of the field calibration process is realized and the calibration efficiency is accelerated by combining the ideas of mechanism control, data control and model predictive control.

4. Conclusion

The establishment of PipeChina adopts the operation mode of X+1+X, which separates the upstream and downstream, so that the market can fully compete. The guarantee of multi-party fairness lies in the measurement of trade handover, meanwhile the rapid and accurate calibration of the flowmeter is of great significance to the client or the calibration station. With the goal of improving the calibration efficiency of calibration station and improving the intelligence of calibration process, this paper studies the automatic control of the whole process of calibration station. The practice shows that the GT-ST method can identify the flow of the calibration station and automatically switch to the calibration process. At the same time, the mechanism model based on the model predictive control idea and the control algorithm of the BP neural network model make the open-loop optimization close-loop, which makes it possible to adjust the calibration flow. The control algorithm is verified by the simulation platform. The algorithm automatically controls the whole calibration process, and the case results meet the calibration specification with an error of less than 5%. The field implementation shows that the intelligent calibration controller of the natural gas calibration deployed in the field achieves the automatic control of the whole process of the calibration station, accelerates the calibration efficiency of the natural gas flowmeter and improves the intelligent level of the calibration process.

References

[1] He Huang, Xu Gang, Hancheng Yu, et al. Current situation and progress of natural gas flow measurement technology at home and abroad[J]. Natural Gas And Oil, 2009, 27(02): 42-47.

[2] Wei Han, Xingchuan Chen, Chuanbo Zheng, et al. Preliminary exploration on the application of intelligent flowmeter calibration system[J]. Industrial Measurement, 2018, 28(05): 80-83.

[3] Zhe Liu, Duocai Wang, Xingpeng Jiang, et al. Research and practice on Intellectualization of natural gas measurement and calibration[J]. Industrial Measurement, 2020, 30(02): 9-11. DOI:10.13228/j.boyuan.issn1002-1183.2019.0228.

[4] Hongwei Zheng, Zhe Liu, Yan Wu. Exploration and prospect of the intelligent metrological calibration technology of natural gas[J]. Oil & Gas Storage and Transportation, 2021, 40(03): 287-292+318.

[5] Kai Wen, Xiong Yin, Zhe Guo, et al. Study on Active Control Method of Natural Gas Large Flow Metrological Calibration Process[J]. Oil-Gas Field Surface Engineering, 2019, 38(10): 57-63.

[6] Xu Han, Nan Sun, Xiran Zhang, et al. Establishment of simulation model and optimization of processnoperation for calibration station of natural gas flowmeter[J]. Oil & Gas Storage and Transportation, 2021, 40(02): 208-214.

[7] Yan Wu, Chaofan Song, Zhe Liu, et al. Practice of intelligent quality control technology in calibration of natural gas flowmeter[J]. Oil & Gas Storage and Transportation, 2021, 40(06): 637-642.

[8] Kai Wen, Xu Han, Can Li, et al. Neural network based intelligent control system of natural gas flowmeter calibration process[J]. Natural Gas Industry, 2021, 41(07): 124-133.

[9] Yin Xiong, Wen Kai, Wu Yan, et al. A machine learning-based surrogate model for the rapid control of piping flow: Application to a natural gas flowmeter calibration system[J]. Journal of Natural Gas Science and Engineering, 2022, 98.

[10] Modarres M, Cheon S W. Function-centered modeling of engineering systems using the

goal tree–success tree technique and functional primitives[J]. Reliability Engineering & System Safety, 1999, 64(2): 181-200.

[11] Ning Xinxian.Study on Fault diagnosis Method of Nuclear Power Plant Based on GT-ST and MFM[D].Harbin Enginerring University.2009

[12] Bo Zhao. Nerve Network Predictive Control Crude Oil Heater Stove Temperature[D]. Liaoning: Liaoning Institute of Technology, 2007.

[13] Bao Liu, Jinying Yang, Zongde Wu. Research on Wavelet Neural Network Predictive Control and Its Application in Oilfield Production System[J/OL]. Control Engineering of China: 1-7[2022-03-15]. DOI:10.14107/j.cnki.kzgc.CPCC2020-215.

[14] Lei Zhang, Xiang Xu, Bin Chen. Multi-variable model predictive control of crude oil heat exchanger networks[J]. Computers and Applied Chemistry, 2012, 29(02): 237-239. DOI:10.16866/j.com.app.chem2012.02.027.

[15] Dan Wang, Xiufeng Pang, Wei Wang. Review and Prospect of the Application of Model Predictive Control in Building HVAC System[J]. BUILDING SCIENCE, 2021, 37(12): 111-119+130. DOI:10.13614/j.cnki.11-1962/tu.2021.12.16.

[16] Guangnan Li, Hongtao Ye, Wenguang Luo. Longitudinal motion control of unmanned vehicle based on IPSO-MPC[J]. JOURNAL OF GUANGXI UNIVERSITY OF SCIENCE AND TECHNOLGY, 2022, 33(01): 94-100+109. DOI:10.16375/j.cnki.cn45-1395/t.2022.01.014.

[17] Shengli Du, Qingda Zhang, Boqi Cao, et al. A Review of Model Predictive Control for Urban Wastewater Treatment Process[J]. Information and Control 2022, 51(01): 41-53. DOI:10.13976/j.cnki.xk.2022.0101.