

Application Research of Cyber-Physical Systems in Transformer Voltage Regulation Control: Postprint

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Abstract

In view of the fact that existing transformer voltage regulation methods are constrained by tap-changer position limitations, and that voltage adjustment decisions are based on voltage curves determined by dispatching departments, it is difficult to achieve flexible, efficient, and high-precision stabilization of transformer output voltage. To better address voltage deviation issues during transformer operation, a dynamic voltage stabilization regulation method based on cyber-physical fusion systems is proposed. The physical model and information model of the transformer are established; through mutual mapping between physical parameters and information attributes, dynamic linking is utilized to integrate the physical and information models on a unified simulation platform, thereby constructing a cyber-physical fusion system model for the transformer. Through a real-time feedback mechanism from information quantities to physical quantities, automatic adjustment of the primary-to-secondary coil turns ratio is controlled to achieve transformer output voltage stabilization. Simulation experimental results demonstrate that the cyber-physical fusion method possesses certain effectiveness in applications of transformer output voltage stabilization regulation.

Full Text

Application of Cyber-Physical Systems in Transformer Constant Voltage Regulation Control

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Abstract

Existing transformer voltage regulation methods are constrained by tap position limitations, and voltage adjustment decisions are based on voltage curves determined by dispatching departments, making it difficult to achieve flexible, efficient, and high-precision stabilization of transformer output voltage. To better address voltage deviation issues during transformer operation, this paper proposes a dynamic voltage regulation method based on cyber-physical fusion systems. The physical and information models of the transformer are established, and through mutual mapping between physical parameters and information attributes, dynamic linking integrates the physical and information models on a unified simulation platform to construct a transformer cyber-physical fusion system model. Through a real-time feedback mechanism where information quantities act on physical quantities, the automatic adjustment of the primary-to-secondary winding turns ratio is controlled to achieve stable transformer output voltage. Simulation results demonstrate the effectiveness of the cyber-physical fusion method in stabilizing transformer output voltage.

Keywords: cyber-physical system; power transformer; physical model; information model; constant voltage regulation; optimized control

0 Introduction

The stability of transformer output voltage is critical to power quality and has significant implications for the safe and economical operation of power systems as well as for ensuring the service life of electrical equipment. Abnormal voltage deviations during transformer operation caused by various factors not only degrade equipment performance but also affect the overall safety and stability of the power system. Effective transformer regulation to ensure continuous stable output represents an important problem that needs to be addressed in transformer research.

Transformer output voltage regulation methods fall into two categories: no-load voltage regulation and on-load voltage regulation, implemented through off-circuit tap changers and mechanical on-load tap changers, respectively. No-load voltage regulation requires transformer outage during operation, causing inconvenience and interrupting power system operation. Therefore, on-load voltage regulation is currently preferred. Reference [?] proposed a non-impact on-load voltage regulation method using power electronic devices as tap switches, determining the regulation timing through load impedance angles. Reference [?] analyzed the selection method for tap changing operations when raising or lowering transformer output voltage using on-load voltage regulation. Reference [?] designed a microcontroller-based adjustable reactor for voltage regulation through mechanical transmission, though its effectiveness was unsatisfactory for low-voltage conditions. While on-load voltage regulation is widely used and extensively researched, tap position limitations and regulation decisions based on dispatching department voltage curves result in low regulation precision and

certain time delays [?].

Consequently, this research applies cyber-physical system fusion technology to power transformers, establishing a transformer cyber-physical system model that utilizes information flow feedback control of the physical network to achieve efficient, flexible real-time voltage regulation, improve voltage regulation precision, and ensure output voltage stability. Through simulation using a typical power system model, the applicability, universality, and convenience of transformer cyber-physical system modeling in power grid applications are verified.

1 Cyber-Physical Systems

A Cyber-Physical System (CPS) represents the next-generation engineering system that achieves deep integration of computing, communication, and control technologies based on physical space entity networks [?, ?]. Unlike traditional embedded real-time systems and wireless sensor networks, CPS technology no longer simply achieves required performance through optimized utilization of computer hardware and software resources, but rather enhances various aspects of physical system performance through full exploitation and utilization of information quantities [?].

Power systems constitute an important application domain for CPS technology. Cyber-Physical Power Systems (CPPS) or Cyber-Physical Energy Systems (CPES) are considered the fundamental architecture of next-generation power systems. Their main characteristics include: reliability—CPPS must be robust during system faults or environmental changes; autonomy—when problems occur, CPPS can automatically execute predefined solutions through closed-loop control; high integration—CPPS must achieve high integration of computing and physical dynamic processes through network communication or embedded real-time systems; and multi-scale complexity in time and space—fusion of continuous physical systems and discrete information systems [?]. With the continuous advancement of power grid intelligence [?], CPPS has become a research hotspot in the power industry. Current research by scholars both domestically and internationally focuses primarily on: CPPS modeling methods and formal verification, CPPS system analysis methods, and CPPS system control methods [?].

2 Power Transformer Cyber-Physical Fusion System Model

The modeling process for the transformer cyber-physical fusion system is shown in [Figure 1: see original paper]. First, the transformer physical system and information system are analyzed separately to establish their physical dynamic model and information model. After comprehensive comparison and model optimization, mutual mapping between physical model parameters and information model attributes is achieved. Then, integration is performed at the control level and implementation level to establish the transformer cyber-physical fusion system model. At the control level, through information control center access to

and feedback from the physical system, as well as interaction between physical and information systems, the fusion of information and physical systems and the voltage regulation control of transformer output voltage by the transformer cyber-physical system are realized. At the implementation level, the final integration of different implementation approaches for physical and information models establishes the transformer cyber-physical system model on a unified simulation platform.

2.1 Transformer Physical System Modeling

In transformer cyber-physical systems, real-time interaction exists between physical and information quantities, and various physical parameters should be conveniently accessible and transmittable by the system. Based on these principles, a customized s-function module approach is adopted to establish the dynamic physical system model of the power transformer.

First, the physical operating characteristics of the transformer are mathematically analyzed. The principle of transformer load operation is shown in [Figure 2: see original paper] [?]. Where U_1 is the input voltage of the primary winding, R_1 and jX_1 are the resistance and leakage reactance of the primary side, I_1 is the primary side current, R'_2 and jX'_2 are the resistance and leakage reactance of the secondary winding after conversion, Z'_L is the load impedance after conversion, U'_2 is the output voltage of the secondary side after conversion, I'_2 is the secondary side current after conversion, R_m and jX_m are the excitation resistance and excitation reactance of the inductor coil, I_0 is the excitation current, E_1 and E'_2 are the induced electromotive forces generated by the primary winding and the converted secondary winding respectively, and k is the rated turns ratio of the primary and secondary coils. According to Kirchhoff's laws:

$$U_1 = E_1 + I_1 \cdot Z_1 \quad (1)$$

$$U'_2 = E'_2 - I'_2 \cdot Z'_2 \quad (2)$$

$$I_1 = I_0 + I'_2 \quad (3)$$

$$E_1 = k \cdot E'_2 \quad (4)$$

Based on the transformer winding conversion relationship, from equations (1) to (5), we can derive:

$$U'_2 = \frac{k \cdot Z'_L}{Z_1 + k^2 \cdot Z'_2 + Z_m + Z'_L} \cdot U_1 \quad (6)$$

Then the output voltage is:

$$U_2 = \frac{U_2'}{k} = \frac{Z_L'}{Z_1 + k^2 \cdot Z_2' + Z_m + Z_L'} \cdot U_1 \quad (7)$$

According to the above mathematical model of the power transformer, an s-function program file is written to implement the physical system modeling of the transformer.

2.2 Transformer Information System Modeling

The information model for power systems is the Common Information Model (CIM) [?]. When establishing the transformer information system model, the CIM package from IEC61970 is adopted, and UML language is used to describe the CIM model.

Parameters in the transformer physical model must find corresponding attributes in the information model to achieve mutual mapping between physical and information systems. Therefore, when establishing the transformer information model, transformer physical quantities should serve as the benchmark. If no corresponding information attribute exists in the information model, the model must be extended with categories or attributes to satisfy mutual mapping. If attributes in the information model exceed the scope of physical quantity requirements, they are retained.

The transformer information system CIM model established according to these principles [?] is shown in [Figure 3: see original paper]. The transformer information model contains six class packages: PowerTransformer, TapChanger, TransformerWinding, RegulationSchedule, WindingTest, and HeatExchanger. The PowerTransformer class has aggregation relationships with the HeatExchanger and TransformerWinding classes, meaning that heat exchangers and transformer windings are parts of the power transformer. One heat exchanger can only belong to one transformer, while one transformer may contain zero or one heat exchanger. One transformer winding can only belong to one transformer, while one transformer may contain one or more transformer windings. Similar aggregation relationships exist between TapChanger and TransformerWinding. Additionally, simple associations exist between TapChanger and RegulationSchedule (one tap changer can have zero or one regulation schedule, while one regulation schedule may belong to zero, one, or multiple tap changers) and between TransformerWinding and WindingTest.

Each class in the transformer information model has several attributes. Based on the transformer physical dynamic model parameters from Section 2.1, corresponding attributes can be extracted from the information model. Since parameter k (the primary-to-secondary winding turns ratio) in the transformer physical model is not reflected in the transformer CIM model attributes, the TransformerWinding class in the information model is extended with the k

attribute. The mapping relationship between transformer information model attributes and physical model parameters is shown in .

2.3 Transformer Cyber-Physical Fusion System Modeling

To achieve better voltage stabilization, this paper designs a control system that dynamically adjusts the transformer primary-to-secondary winding turns ratio based on the deviation between actual output voltage and rated output voltage to realize stable transformer output [?]. The integrated model of the power transformer cyber-physical system with dynamic control functions is shown in [Figure 4: see original paper]. In the figure, solid lines represent physical quantities and dashed lines represent information quantities. Where U is the transformer primary side input voltage, ΔU is the fluctuation variation added to the input voltage U , U_2 is the transformer output voltage, U_o is the transformer rated output voltage, ΔU_o is the deviation of actual output voltage from rated output voltage, k is the transformer rated primary-to-secondary winding turns ratio, Δk is the turns ratio variation output by the information control module, and k' is the adjusted transformer primary-to-secondary winding turns ratio. The system transmits the information-based intermediate variables Δk and output voltage deviation ΔU_o to the information control module, enabling the information control center to access the physical operation process.

The specific voltage regulation control process is shown in [Figure 5: see original paper]. The system input is the transformer rated input voltage U . During operation, a fluctuation variation ΔU is added to examine the output voltage U_2 deviation. When $\Delta U_o = 0$, the system output voltage U_2 should equal the rated output voltage U_o , and the transformer turns ratio k remains unchanged. When $\Delta U_o \neq 0$, the transformer input voltage changes to $U + \Delta U$, and the deviation between actual output voltage and rated output voltage is ΔU_o . At this point, the program in the information control module determines whether to increase or decrease the turns ratio Δk based on the positive or negative attribute of ΔU_o . If $\Delta U_o > 0$, the turns ratio k needs to be increased; if $\Delta U_o < 0$, the turns ratio k needs to be decreased. According to the turns ratio formula and input/output voltage changes, we can derive:

$$\Delta k = \frac{\Delta U_o}{U_o} \cdot k \quad (8)$$

Then the adjusted transformer primary-to-secondary winding turns ratio is:

$$k' = k \cdot \left(1 + \frac{\Delta U_o}{U_o} \right) \quad (9)$$

After completing real-time dynamic calculations, the information control module feeds back the physical output result k' as an actuating quantity to the

physical dynamic system, thereby achieving stable output on the transformer secondary side.

Since this control system can finely adjust the transformer turns ratio according to minute changes in actual output voltage relative to rated output voltage, without being limited by tap positions, it achieves stepless voltage regulation and therefore provides higher voltage regulation precision than traditional methods.

After establishing the physical and information models separately, a dynamic linking mechanism is required to integrate them on a unified simulation platform. [Figure 6: see original paper] shows the implementation approach for the transformer CPS model. The transformer physical system model is built on the MATLAB platform, while the transformer information system model is built on the Enterprise Architect (EA) platform. Leveraging EA' s capability to convert UML-described CIM class diagrams into non-graphical programming languages such as C++ and Java, the power transformer CIM information model is converted into C++ language programs and operated on the Visual Studio 2010 platform. A bridge connecting the Visual Studio and Matlab simulation platforms is needed to achieve true fusion of physical and information flows in the transformer system. Reference [?] provides an excellent solution to this problem by encapsulating C++ language programs as dynamic link library files that are called on the Matlab platform to achieve a unified simulation platform. Drawing on this approach, this paper generates dynamic link library files from the C++ programs describing the transformer information model and the controller program for adjusting transformer primary-to-secondary winding turns ratio in the Visual Studio environment, and calls these files in the s-function module program describing the transformer physical dynamic characteristics, thereby achieving integration of physical and information models on a unified simulation platform.

3 Simulation Experiments and Results Analysis

The simulation experiments in this paper were conducted using an Intel(R) Core(TM) i7-4710MQ CPU@2.50GHz processor in the Matlab R2015a environment. A typical power grid simulation model was built, including power sources, transmission lines, transformers, and loads, as shown in [Figure 7: see original paper], to examine the performance of the transformer voltage regulation strategy based on CPS modeling in power grid operation.

In [Figure 7: see original paper], the S-Function module represents only the transformer physical dynamic characteristics model without the information model or related information flow control, while the S-Function1 module represents the transformer CPS model that calls the dynamic link library files generated from the CIM information model and information flow control program on top of the physical dynamic characteristics model.

[Figure 8: see original paper] shows the simulation model built using Simulink' s On-Load Tap Changer (OLTC) transformer module. The same parameters were

set for each module in [Figure 6: see original paper] and [Figure 8: see original paper] to compare the voltage regulation effects of ordinary transformers, CPS-based voltage regulation transformers, and traditional OLTC transformers.

The power source voltage was set to 120 V, with a transformer rated turns ratio of 120/25. During the simulation, the input voltage was dynamically adjusted within the range of $\Delta U = \pm 10\%$ to observe the transformer output voltage deviation in [Figure 7: see original paper] and [Figure 8: see original paper]. Among these, $\Delta U = \pm 5\%$ belongs to the allowable regulation range, during which the transformer operates normally. When the input voltage variation exceeds $\pm 5\%$ of the rated voltage, the transformer may enter abnormal operating conditions. The simulation results are shown in , where U is the input voltage, U_{o_P} is the output voltage of the ordinary transformer model without information model participation, U_{o_OLTC} is the output voltage of the traditional on-load tap changer transformer model, and U_{o_CP} is the output voltage of the on-load tap changer transformer model based on CPS modeling.

The trend of output voltage variation with input voltage is shown in [Figure 9: see original paper]. The black solid line represents the output voltage variation curve of the transformer physical model without information quantity participation, the blue dash-dot line represents the output voltage variation curve of the OLTC transformer simulation model, and the red dashed line represents the output voltage variation curve of the on-load tap changer method based on CPS modeling.

From the simulation results, it can be seen that for the transformer physical model without information quantity participation, when the input voltage varies within $\pm 5\%$, the output voltage changes significantly, with a fluctuation range reaching 0.96%~5.04%. The OLTC transformer, having on-load voltage regulation capability, can control its output voltage fluctuation range within 0.25%~1.38%. The CPS-based transformer on-load voltage regulation method can stabilize the output voltage well near the rated voltage, with a fluctuation range of only 0.04%~0.21%, improving voltage regulation precision. When the transformer input voltage exceeds $\pm 5\%$ of the rated voltage, for the transformer physical model without information quantity participation, the output voltage variation with input voltage can reach up to 9.04%, exceeding the allowable voltage deviation range. The OLTC transformer output voltage fluctuation range also reaches 1.52%~2.5%. In contrast, the CPS-based transformer voltage regulation method can still control the output voltage deviation within 0.22%~0.91%, demonstrating good voltage stabilization effects. Thus, the CPS-based transformer on-load voltage regulation method can optimize voltage quality regulation through flexible control of information quantities, enabling more stable output.

4 Conclusion

Current transformer voltage regulation methods still have certain drawbacks. To address these issues, this paper proposes a transformer voltage regulation method based on cyber-physical fusion. By establishing a transformer CPS model and fully utilizing the feedback control effect of information quantities on physical quantities, the transformer primary-to-secondary winding turns ratio is dynamically adjusted in real time to achieve automatic voltage stabilization, overcoming reliability issues of existing voltage regulation methods and improving voltage regulation precision. However, in engineering applications, external circuit devices capable of contactless stepless voltage regulation must be coordinated to achieve high-precision voltage regulation control.

This research provides an approach for applying CPS technology to power transformers. Future work can continue in-depth research based on this foundation, enabling transformers to possess self-awareness, prediction, and self-configuration capabilities through CPS technology to achieve optimized coordinated control and effective health management of power transformers.

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