

Review of Online State Measurement and Identification Technology for Synchronous Generator Excitation Systems: Postprint

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Date: 2019-03-05T00:00:00+00:00

Abstract

This paper categorizes online measurement and identification of excitation system parameters into three stages: real-time information acquisition, online parameter identification, and online performance evaluation. It analyzes the characteristics of each stage and explores the development directions of online measurement and identification technology for excitation system parameters. The results indicate that the real-time information acquisition stage of excitation systems has achieved substantial improvements in measurement time synchronization and spatial coverage; however, the new online monitoring technology represented by intelligent components and its underlying application theory require further investigation. Parameter identification based on power grid disturbances demonstrates strong capabilities in nonlinear component parameter identification and noise suppression. While this approach can satisfy current requirements for online system parameter identification, enhancing online identification accuracy necessitates research into novel identification algorithms and classified identification strategies. The existing theoretical framework for excitation system performance evaluation primarily emphasizes qualification benchmarking, and foundational research supporting hierarchical system performance evaluation remains to be developed.

Full Text

Overview on On-Line Status Identification Technology of Synchronous Generator Excitation System

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Abstract

This paper divides the online measurement and identification of excitation system parameters into three stages: real-time information acquisition, online parameter identification, and online performance evaluation. It analyzes the characteristics of each stage and discusses the development direction of excitation system parameter online identification technology. The results show that the real-time information acquisition stage has achieved significant improvements in measurement time synchronization and spatial extensibility. However, the basic theories and application fundamentals of new online monitoring technologies, represented by intelligent components, require further research. Parameter identification based on grid disturbances exhibits strong capability in nonlinear component parameter identification and noise suppression, which can meet current system online identification needs. To further improve online identification accuracy, research on new identification algorithms and classification identification strategies is necessary. The existing theoretical framework for excitation system performance evaluation primarily focuses on qualitative benchmarking, and foundational research supporting graded performance evaluation of the system needs to be developed.

Keywords: Synchronous generator, excitation system, online measurement and identification, performance evaluation

1 Introduction

The accuracy of excitation system model parameter settings directly affects the precision and reliability of power system stability calculations [1]. Currently, the excitation system model parameters used by grid dispatching departments are generally determined through offline testing of the excitation system. Theoretical analysis reveals that offline measurement and identification suffer from discrepancies between test conditions and actual operating conditions, failing to accurately reflect the mutual response among system components and the actual operating status of generators, resulting in low equivalence and timeliness [2]. In contrast, online measurement and identification can directly account for the combined effects of generator operating conditions and environmental factors, yielding parameter identification values that more closely approximate the actual parameters of the excitation system. This facilitates timely monitoring of the excitation system's operational status by grid dispatching departments and represents a current research hotspot and challenge in this field [3].

Online measurement and identification of synchronous generator excitation system model parameters can be divided into three stages [4-6]: First is the real-time information acquisition stage, which primarily implements online monitoring of excitation system status characterization data. Second is the online parameter identification stage, which inputs the online measured excitation system data into system models for parameter identification. Third is the online performance evaluation stage, which achieves comprehensive assessment of exci-

tation system performance through comparative analysis of behavioral characteristics between dynamic simulation models and the actual excitation system. This paper reviews the research status of these three stages and analyzes future research directions.

2 Real-Time Information Acquisition Stage Research Status

2.1 Traditional Online Monitoring Technology

The monitoring methods currently widely applied in China's power systems mainly include the Supervisory Control and Data Acquisition/Energy Management System (SCADA/EMS) for monitoring and controlling steady-state system operation, and various Digital Fault Recorders (DFR) for recording system transient processes.

The SCADA/EMS based on supervisory control and data acquisition can collect operational quantities such as voltage/current RMS values, active/reactive power during steady-state or quasi-steady-state operation of the power system, and upload them to the dispatching information center within the local area network hierarchy. This primarily includes system state estimation, network topology analysis, static faults, and various information from automatic recording devices during oscillations [8]. DFRs installed at network nodes record the overall variation process of node voltage, current, active power, reactive power, and system frequency during system fluctuations. DFRs installed at generator nodes record relevant data including terminal voltage, terminal current, active power, reactive power, unit speed, excitation voltage, and excitation current during system fluctuations and unit faults. Digital fault recorders mainly consist of acquisition modules and management analysis modules: the acquisition module completes waveform data acquisition, analysis and calculation, and waveform start discrimination; the management analysis module completes data recording, analysis and management, fault type analysis, fault location, and fault reproduction functions. The device structure block diagram is shown in Figure 1 [Figure 1: see original paper] [9].

It is worth noting that although SCADA/EMS and DFR have relatively mature development in system real-time monitoring, they currently share a common deficiency: the lack of accurate time coordinates for data from different locations. The recorded data is only valid locally, making it difficult to adapt to the progressively expanding analysis of power system dynamic behavior [10].

2.2 Phasor Measurement Unit Technology

The Phasor Measurement Unit (PMU) based on the Global Positioning System (GPS) provides a brand-new data source and technical platform for online monitoring of power grid components such as generators [11]. When power grid disturbances occur, GPS/PMU monitoring devices can utilize the timing

function of GPS and AC signals output by power frequency band-pass filters to track system frequency information in real time. The sampling pulse generator divides pulses into a series of pulse sequences that can trigger converters for analog-to-digital conversion. The microprocessor calculates phasor values for each unit based on Fourier transform principles and provides dynamic synchronous phasor data of the generator system in phasor form, including terminal voltage/current phasors, active/reactive power, excitation voltage/current, internal electromotive force power angle, and other information. Its structural principle is shown in Figure 2 [Figure 2: see original paper] [12].

The difference between GPS/PMU monitoring devices and traditional Remote Terminal Unit (RTU) measurements is that measurement values from various PMUs can be synchronized to the same time coordinate, facilitating direct acquisition of effective values of each state quantity and phase relationships between different state quantities. This offers characteristics of high synchronization, high measurement accuracy, and fast data update [13].

With the gradual improvement of power system measurement requirements for time synchronization and spatial wide-area coverage, the Wide Area Measurement System (WAMS) based on PMU has emerged. PMU/WAMS mainly consists of PMUs located at substations, communication systems, and control systems at dispatching centers. It monitors the operational status of the power grid online based on real-time dynamic measurement data from key substations in the grid, issues limit violation (static and dynamic) alarms when abnormalities occur in system voltage, phase angle, or frequency, and observes, identifies, and analyzes abnormal operating states, characteristic signals, and fault types of the system. Through observation and analysis, it provides technical basis for the formulation of power system stability control strategies. PMU/WAMS technology has achieved substantial improvements in real-time data monitoring and measurement scope, laying a solid foundation for online measurement of generator power angles across the entire network and analysis and control of wide-area power systems [13-15].

3 Parameter Online Identification Stage Research Status

3.1 Artificial Disturbance Excitation Method

Parameter online identification tests under artificial disturbance excitation require that external excitation signals do not affect the normal operation of generators, with research primarily focusing on excitation signal design, data preprocessing, identification algorithms, and handling of nonlinear characteristics [16]. Currently, parameter online identification under artificial disturbance is mainly divided into online frequency-domain identification methods and online time-domain identification methods.

The online frequency-domain method is a typical online frequency-domain identification approach under artificial disturbance excitation. This method applies external disturbance signals during unit operation and uses dynamic fitting

methods to obtain parameters. The identification process is shown in Figure 3 [Figure 3: see original paper] [17-18]. First, real-time sampling and Fast Fourier Transformation (FFT) are used to convert system input/output signals into frequency-domain signals, and the system's frequency characteristics (amplitude-frequency and phase-frequency characteristics) are obtained based on the Wiener-Hopf equation. Then, dynamic fitting methods (least squares method, improved Levy method, Kalman filtering method, maximum likelihood method) are employed to extract model parameters from the frequency response curves. Field test results demonstrate that the measured phase-frequency and amplitude-frequency characteristics of each segment basically match the curves fitted with the obtained parameters, with mean square errors less than 5%, meeting parameter error requirements and verifying the correctness and reliability of the test method. This method has been successfully applied to online parameter identification of excitation systems for large turbine and hydroelectric generator units.

The online time-domain identification method first performs related operations such as integration, filtering, and orthogonal transformation on the input/output sequences of the actual system. It then establishes difference equations with specific parameters as identification objects, and obtains characteristic parameters with physical meaning through various direct identification methods such as time-domain least squares method, state filtering method, Block Pulse Function (BPF) method, and Piecewise Linear Polynomial Function (PLPF) method. Subsequently, the output response of the identification object is derived from the input dynamic excitation signals and difference equations, and the difference equation model quality is evaluated by comparing differences between the system's actual output response and the model-calculated output response. Finally, the difference equation model is converted into the mathematical model required by the system, such as transfer function models or state-space models. Its parameter identification flowchart is shown in Figure 4 [Figure 4: see original paper] [19]. Power system researchers and engineering technicians are accustomed to using parameters with clear physical meaning in calculations and analyses. From the perspective of identification operation procedures, the parameter online time-domain identification method is more convenient and has been more widely applied in generator excitation system parameter identification.

Both the online frequency-domain and time-domain identification methods under artificial disturbance have clear principles and are convenient to implement, gaining extensive application in practical excitation system parameter online identification. Analysis results indicate that the online frequency-domain identification method is based on FFT, and its leakage, aliasing, and fence effects can cause significant errors. In contrast, parameter identification modeling using direct time-domain analysis methods offers advantages of high precision and fast speed. The shortcomings of both methods lie in their inability to effectively solve problems such as high-order nonlinear component parameter identification and noise suppression in excitation systems.

3.2 Grid Disturbance Excitation Method

Compared with parameter online identification through artificially applied excitation, parameter identification using dynamic process data of the excitation system under grid disturbance excitation requires no testing and only needs effective measurement equipment to record the dynamic process of the excitation system [20-21]. Therefore, parameter online identification based on grid disturbance excitation possesses high research value and engineering application value, attracting widespread attention from scholars.

Advanced intelligent identification algorithms constitute the core of online parameter identification for excitation systems under grid disturbances. Currently, the main parameter online identification algorithms based on grid disturbances include Genetic Algorithm (GA) and neural network observation methods. GA directly utilizes natural system disturbances for parameter identification: first, it establishes transfer functions of the original excitation system model and standard model along with structural block diagrams of each nonlinear component; then it encodes each parameter to be identified in the excitation system standard model, including encoding of nonlinear component parameters; through continuous optimization by GA, it finally obtains the optimal parameters for the excitation system standard model. Its parameter identification flowchart is shown in Figure 5 [Figure 5: see original paper] [22-23].

The GA identification method fully considers the nonlinear characteristics of excitation systems and can effectively solve parameter identification problems for nonlinear components in excitation systems. Meanwhile, GA is a parallel algorithm capable of global search in the data space and can find global optimal solutions with high probability, facilitating excitation system parameter identification.

The neural network observation method requires minimal human intervention. It directly addresses the nonlinear characteristics of generator parameters and utilizes neural networks to simulate complex nonlinear parameters, enabling effective tracking of generator parameter variations. Moreover, neural networks possess self-learning and adaptive functions, allowing continuous training during actual excitation system operation and online observation of synchronous generator excitation system dynamic characteristics [24-25].

4 Excitation System Performance Online Evaluation Stage Research Status

Related research indicates that the regulation characteristics of generator excitation systems are directly related to the steady-state and transient characteristics of power systems. For excitation regulation systems, increasing gain and reducing time constants can improve generator voltage regulation accuracy, reduce dynamic overvoltage of generator units, and enhance power system voltage stability and static stability. Higher strong excitation multiples can improve power

system transient stability [26]. Accurate evaluation of excitation system regulation performance is of great significance for the safe operation of power systems.

Excitation system regulation performance indicators can be divided into large-disturbance dynamic performance indicators and small-disturbance dynamic performance indicators. Large-disturbance dynamic performance indicators refer to performance indicators when the disturbance signal is large enough to cause regulation to reach limited amplitudes, namely the dynamic performance indicators of excitation system limiters. Small-disturbance dynamic performance indicators refer to performance indicators when the disturbance signal is very small and excitation regulation operates in the linear region, including dynamic damping characteristics under low-frequency oscillations, load step response characteristics, and closed-loop characteristics. Among these, excitation system limiter dynamic performance evaluation and excitation system dynamic damping performance evaluation theories are relatively mature, with related assessments covering the main performance indicators of excitation system stability and rapidity [27], specifically evaluating the rationality of control parameters and providing reliable references for the location analysis and control of negative damping low-frequency oscillation sources.

In a sense, excitation system performance evaluation has already involved component-level assessment. However, this technology remains in its initial research stage, and research work on related characteristic analysis methods and performance indicators for accurately evaluating the regulation performance of each component still needs to be developed.

5 Discussion on Research Directions

As described above, extensive research has been conducted both domestically and internationally on excitation system real-time information acquisition technology, excitation system parameter online identification methods, and performance evaluation of various excitation system components, yielding abundant research results that have played a significant role in excitation system performance evaluation and safe, stable grid operation. With the large-scale integration of volatile renewable energy sources and the ever-expanding scale of power grids, power system operating conditions are becoming increasingly complex, and the demand for more accurate acquisition of excitation system performance parameters and status is becoming more urgent [30-31]. Continuing to optimize and improve existing excitation system status online identification technology remains of important engineering value and practical significance. Meanwhile, this paper believes that the following aspects also warrant attention:

5.1 Excitation System Intelligent Component Technology

The so-called excitation system intelligent component refers to an Intelligent Electronic Device (IED) based on GPS or BeiDou timing systems that can acquire, record, and provide real-time and historical data including excitation

transformer status, generator unit status, regulator status, power unit status, and generator excitation system status. The architecture of the excitation system intelligent component is shown in Figure 6 [Figure 6: see original paper].

In theory, excitation system intelligent component technology can dynamically record information data from various components of the excitation system, providing fundamental data for refined identification and analysis of parameters for each system module. It can monitor unit disturbances and their excitation system response processes, providing data support for calculation and analysis of excitation system dynamic and static performance indicators, thereby achieving accurate evaluation of excitation system regulation performance. Additionally, excitation system intelligent component technology can provide comprehensive dynamic fundamental data of excitation systems for generator-grid coordination optimization, which also holds important value for power grid operation mode stability analysis and system simulation model validation [32-33].

In the excitation system real-time information acquisition stage, intelligent component technology represents a new approach, and its application fundamental theories and key technologies warrant attention.

5.2 Component-Level Feature Parameter Online Identification

Parameter online identification under grid disturbances effectively solves problems such as high-order nonlinear component parameter identification and noise signal suppression, offering advantages of simple methodology and no requirement for artificially applied interference signals. However, current research results on excitation system parameter identification under grid disturbances focus on overall identification of excitation system parameters, performing holistic parameter identification of the excitation system through online acquisition of unit disturbance process curves and their dynamic response curves. Research shows that the overall characteristics of excitation systems are relatively complex, and parameter identification results obtained using this method have strong uncertainties. Moreover, this method takes overall system characteristics as the research object and cannot provide grid dispatching with more parameter identification results concerning the internal operation of excitation systems, resulting in non-unique parameter identification results and difficulty in accurately reflecting the performance of various system components [34-35].

Independent identification of parameters for each excitation system module can be achieved through excitation system analysis and decoupling, enabling independent identification of component parameters. This method, based on the regulation characteristics of each component, uses different parameter identification algorithms to identify system parameters in a targeted manner, which is conducive to improving parameter identification accuracy and result uniqueness. It can provide more accurate data support for real-time, independent evaluation of the working status of various excitation system components.

Currently, related work on independent identification of parameters for each

module of excitation systems based on grid disturbances is rarely conducted. To achieve independent identification of parameters for each system component, it is first necessary to propose new technologies and identification algorithms for excitation system decoupling and parameter screening to enable rapid and accurate identification of parameters for each excitation system module [36]. Additionally, this identification method has high requirements for signal acquisition technology. Compared with traditional identification methods that monitor generator terminal dynamic information data online, this method also requires setting up multiple measurement points inside the excitation system to accurately identify parameters of various excitation system components by acquiring real-time information data from components such as excitation limiters, voltage regulators, and power system stabilizers.

5.3 Graded Performance Evaluation of Excitation Systems

To adapt to increasingly complex power system operating conditions and system performance evaluation requirements under different objectives, researchers believe that a graded evaluation system for various excitation system components should be established. First, taking each excitation system component as the research object, the key factors for performance evaluation of each component are arranged hierarchically, with weights established for each factor based on its role and importance in excitation system performance. Then, according to evaluation requirements, the performance of each excitation system component is divided into multiple grades, such as excellent, good, qualified, unqualified, and poor. Next, the graded evaluation system for each system component is used to quantitatively describe the regulation performance of each component, obtaining accurate evaluation results for each component. Finally, correlation analysis between component performance and overall system performance is conducted. By analyzing the optimization degree of each component's regulation performance on overall system performance, the level of the overall system evaluation result is established.

Excitation system performance evaluation is influenced by multiple factors. Simply determining whether the equivalent dynamic performance of the excitation system is qualified can no longer fully satisfy the needs of power system safe and stable operation and increasingly precise evaluation requirements. Taking excitation system dynamic damping performance evaluation as an example, merely determining whether the damping coefficient meets standards cannot specifically judge the damping performance of the excitation system. Different parameter values that meet standards can exhibit different performance characteristics in terms of stability and rapidity for the same excitation system. Therefore, it is necessary to introduce more indicator systems that characterize performance quality to provide more accurate evaluation basis for assessing excitation system regulation performance under different operating conditions. Additionally, the regulation performance of various excitation system components has different degrees of impact on overall system regulation. However, the existing excitation

system performance evaluation system is only suitable for determining whether parameters of various system components are within error ranges and cannot accurately evaluate the optimization degree of qualified parameters of each component on overall system performance [37-38].

Constructing a graded performance evaluation system for various excitation system components can more accurately assess the working status of excitation systems, providing more comprehensive basis for guiding excitation system parameter optimization and risk assessment of power system operation modes.

6 Conclusion

Online measurement and identification of synchronous generator excitation system parameters mainly includes three stages: real-time information acquisition of excitation systems, online parameter identification, and online performance evaluation. Intelligent component technology provides new ideas for excitation system information monitoring, but this technology is still in its initial stage, and its application fundamental theories and key technologies require in-depth research. Parameter online identification based on grid disturbances can effectively solve problems such as nonlinear component parameter identification and noise suppression, but further research is needed in system functional component decoupling and parameter screening. Additionally, research on excitation system performance online evaluation should establish a graded performance evaluation system to adapt to increasingly complex power system operating conditions and system performance evaluation requirements under different objectives.

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