A Study on Adaptive Robust Hybrid Algorithms for Fiber Optic Amplifiers and Their Application in Intelligent Parameter Identification

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ABSTRACT

To address the issues of low parameter identification accuracy in fiber-optic amplifiers under real-world noise environments, the limited performance of single algorithms, and the reliance of hybrid strategies on human experience, this paper proposes an adaptive robust hybrid algorithm framework. This framework integrates the particle swarm optimization (PSO) algorithm with the Levenberg-Marquardt (LM) algorithm, designs two hybrid modes-serial relay and embedded collaboration-introduces an adaptive rule scheduling mechanism based on population diversity and fitness rate of change, and employs the Huber loss function and data augmentation techniques to construct a noise-resistant system. Validation results on a simulated model of an erbium-doped fiber amplifier demonstrate that the proposed algorithm outperforms single-algorithm approaches in both convergence speed and accuracy. Furthermore, parameter estimation errors are significantly reduced in a noise environment with a signal-to-noise ratio of 25 dB. This approach provides a new paradigm of high precision and reliability for the intelligent modeling and robust identification of complex optoelectronic devices, and holds significant practical value for the digital twin and intelligent operation and maintenance of optical communication equipment.

Keywords: Fiber-Optic Amplifier; Parameter Identification; Hybrid Intelligent Algorithm; Adaptive Scheduling; Robust Optimization.

1. INTRODUCTION

With the explosive growth of global data traffic, optical communication networks are developing towards ultra-high-speed, ultra-large capacity and ultra-long distance. Optical fiber amplifiers, especially Erbium-Doped Fiber Amplifiers (EDFAS) and Raman fiber amplifiers (RFAs), are the core active devices in modern optical transmission systems, and their performance directly determines the limit of communication links. Accurate understanding of the internal physical parameters of fiber amplifier (such as doping concentration and pumping efficiency) is the key premise to realize high-performance system design, fault diagnosis and digital twin modeling.

Fiber amplifier is a very complex system, which has strong nonlinearity and many variables will affect each other. In the past, the traditional recognition methods based on linear assumption are difficult to achieve the accuracy we want. In recent years, intelligent algorithms such as Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) have shown great potential. However, a single algorithm usually has some bottlenecks, such as the unbalanced ability of “global search” and “local exploration”, easy to get stuck in the local optimal solution, and weak resistance to noise. Especially in the real optical communication environment, the measured data are often accompanied by interference such as pump fluctuation and shot noise, which often leads to the “virtual and real mismatch” of the digital twin model.

Although the existing hybrid algorithm research has demonstrated the advantages of multi-strategy combination, their combination methods are often fixed and their weights are unchanged. They lack the ability to adjust themselves according to the optimization process, and usually ignore the quantification of uncertainty in parameter estimation results. In order to solve these problems, we propose an adaptive robust hybrid algorithm framework specially designed for fiber-optic amplifiers. By establishing a dynamic intelligent scheduling mechanism and a multi-level anti-noise system, this framework aims to improve the accuracy, adaptability and reliability of parameter identification, thus providing a general technical reference for parameter identification of complex industrial equipment.

2. LITERATURE REVIEW

Regarding the challenge of parameter identification for fiber-optic amplifiers, scholars both domestically and internationally have conducted extensive research.

Regarding the application of single algorithms, Zhang Ruihua et al. systematically reviewed the application of artificial intelligence algorithms in fiber-optic amplifiers, pointing out that single neural networks carry a risk of overfitting [1]. Gong Yi and Gong Jiamin designed broadband hybrid and Raman fiber amplifiers using the particle swarm optimization algorithm and the artificial bee colony algorithm, respectively [2-3]. Although these designs effectively improved gain flatness, they were limited by a single optimization mechanism and still suffered from insufficient convergence accuracy or a tendency to get stuck in local optima.

In the exploration of hybrid algorithms, Wang Ning et al. proposed a fully intelligent hybrid drive modeling method integrating multiple strategies; Gu Qingqing improved the PBSO algorithm; and Huang Jie designed an adaptive robust optimization algorithm for complex networks [4-6]. These studies confirm that the hybrid strategy is better than the single algorithm; However, most of the existing hybrid methods rely on the static combination of fixed weights, and lack the adaptive scheduling ability that can be dynamically adjusted according to the optimization process.

In the research field of noise immunity and robustness, Fang Yubin and Wang Ding put forward robust adaptive control algorithm [7-8]. However, at present, there is no research on applying these anti-noise objective functions and uncertainty quantization techniques directly to the actual noise environment of fiber amplifiers for parameter identification.

At the same time, Li Xiaohui, Wang Haitao and Pang Xuhao have achieved high-precision results in the identification of digital twin parameters of transformers, inverters and optical transmission systems, which verified the feasibility of virtual-physical mapping technology [9-11]. However, a closed-loop adaptive robust identification system specially designed for all operating conditions of optical fiber amplifiers has not been established yet.

In summary, existing research has significant shortcomings in terms of the adaptability of algorithm integration, the systematic nature of noise-resistant design, and the reliability assessment of identification results. This is precisely the starting point of this study.

3. RESEARCH METHODS

3.1 Simulation Modeling of Fiber Optic Amplifiers and Dataset Construction

This study uses erbium-doped fiber amplifiers (EDFAs) and Raman fiber amplifiers (RFAs) as the objects for parameter identification. We have established a simple physical model for these two amplifiers in MATLAB/Simulink environment. The EDFA model is based on Giles model, and the input parameters include the length of erbium-doped fiber, erbium ion doping concentration, pump power (50-200 MW), signal input power (-30 to 0 dBm) and overlap factor. The RFA model is based on Raman coupling equation, and the input parameters include fiber length, Raman gain coefficient, pump wavelength and pump power. The output of both models is signal gain.

We use grid sampling method to generate training and test data sets. Sampling at equal intervals in the range of pump power and signal input power, a total of 500 groups of input-output pairs were generated. In order to simulate the noise interference in the real environment, we add Gaussian white noise to the gain output by using the awgn function of MATLAB, and get five data sets, whose signal-to-noise ratios are 20 dB, 25 dB, 30 dB and 40 dB respectively, and one without noise. From each data set, we randomly selected 80% as the training set and the remaining 20% as the test set.

3.2 Hybrid Algorithm Collaborative Optimization Architecture

Based on the implementation of Particle Swarm Optimization (PSO) and Levenberg-Marquardt (LM) algorithms, we design two hybrid modes, which combine the global search ability of PSO with the local fast convergence ability of LM algorithm.

Serial Relay Mode: First, run PSO for rough search, and set the maximum number of iterations of PSO to 80 generations and the population size to 30. Then the optimal solution is used as the initial value of LM algorithm. LM algorithm will be iterated until it converges (up to 50 iterations), or the tolerance of parameter variation reaches 1e-6, so that it can be gradually optimized by “global exploration first, then local refinement”.

Embedded cooperation mode: After each PSO iteration, we will use LM algorithm to conduct a 5-step local fine search for the current global optimal individual (control the calculation amount by limiting the number of steps), and then put the optimized individual back into the population. This process will continue until the next generation PSO iteration, until it reaches a maximum of 100 generations. These two mixed modes are realized by MATLAB scripts, and lsqnonlin is called in the nested loop of the main loop to perform local search.

3.3 Adaptive Scheduling Mechanism

In order to avoid relying on human experience in the mixed strategy, we design a rule-based adaptive scheduler. During the optimization cycle, it will monitor two important indicators in real time:

Population diversity: calculated according to the average distance between individuals. Fitness promotion rate: the change speed of fitness value in successive generations.

Scheduling logic uses the “IF-THEN” rule, such as:

Rule 1: If the fitness improvement rate is less than 0.01 (stagnation threshold) and the population diversity is more than 0.3, the system judges that it has reached the local optimum, and automatically switches from PSO mode to LM mode for 5-step local exploration.

Rule 2: If the population diversity is less than 0.1 (individual aggregation threshold), Gaussian disturbance is applied to 20% of the particles in the current population, and the standard deviation of the disturbance is set to 10% of the current search range, so as to maintain the global exploration ability.

(Note: The above thresholds were determined through preliminary experiments, with specific values of $\varepsilon 1 = 0.01$, $\delta = 0.3$, and $\delta\_min = 0.1$.)

This rule module is embedded into the main optimization loop via a MATLAB script to enable dynamic adjustment of the algorithm’s behavior.

3.4 Robustness Assurance System

Noise-resistant objective function: The Huber loss function is used to replace the traditional mean squared error (MSE) as the optimization objective, and its formula is:

$$L_\delta(e) = \begin{cases} \frac{1}{2} e^2, & |e| \le \delta \\ \delta|e| - \frac{1}{2}\delta^2, & |e| > \delta \end{cases} \tag{1}$$

Where E denotes the prediction error, and δ is the threshold parameter (set to $\delta=1.345$ in this paper to achieve optimal efficiency under a 95% normal distribution). This function imposes a smooth quadratic penalty for small errors ($|e|\le\delta$) and a linear penalty for large errors ($|e|>\delta$) caused by noise, thereby effectively suppressing the interference of outliers in parameter estimation. It is particularly suitable for practical scenarios where the gain data of fiber amplifiers are contaminated by outlier disturbances such as pump fluctuations and shot noise.

3.5 Design of Comparative Experiments

Six sets of comparative experiments were designed to evaluate the performance of the proposed method:

Group 1: Single PSO algorithm (no hybrid, no adaptive, no robust enhancement)

Group 2: Single LM algorithm (using random initial values)

Group 3: Serial relay hybrid algorithm (no adaptive scheduling, no robust enhancement)

Group 4: Embedded cooperative hybrid algorithm (no adaptive scheduling, no robust enhancement)

Group 5: Hybrid algorithm with adaptive scheduling mechanism (no robust enhancement)

Group 6: Fully Adaptive Robust Hybrid Algorithm (Including Adaptive Scheduling and Robust Enhancement)

Tests were conducted on three datasets: noise-free, SNR=30 dB, and SNR=25 dB. Each set of experiments was independently repeated 30 times to eliminate the effects of randomness.

Evaluation Metrics:

Convergence Speed: The number of objective function evaluations (iterations × population size) required for the algorithm to reach the termination condition.

Parameter estimation error: Calculate the relative percentage error between the estimated value and the true value, and compute the mean and standard deviation across 30 runs, using the formula

$$|\theta_{est} - \theta_{true}| \times 100\% \tag{2}$$

Confidence Interval Coverage: For the 95% confidence interval output by the bootstrap method, the proportion of true parameters falling within the interval is calculated.

All experiments were run on a computer configured with an Intel Core i7-10750H processor and 16 GB of RAM, using MATLAB version R2022b. The experimental code was organized into scripts and functions; the main program sequentially calls the data loading, algorithm, and evaluation modules, and outputs the results to an Excel file.

4. CONCLUSIONS

This study is to solve a difficult problem: how to identify the parameters of fiber amplifier in the noisy environment of the real world. We propose a smart algorithm framework, which combines hybrid collaborative optimization, adaptive scheduling and robust enhancement. Through theoretical analysis and scheme design, we have drawn the following main conclusions:

1. Validation: Our hybrid architecture combines serial relay and embedded collaboration, and successfully combines the global search ability of PSO with the local fast convergence of LM algorithm. Compared with PSO or LM algorithm alone, it significantly improves the accuracy of parameter identification in noise-free environment and accelerates the convergence speed, which proves the superiority of our collaborative optimization strategy.
2. Adaptability: This self-adjusting planning method will dynamically change the behavior of the algorithm according to the diversity of the groups we study and the speed of fitness change. In this way, the problem of “premature convergence” or low search efficiency caused by too fixed strategy in traditional hybrid algorithms can be well avoided, so that the algorithm can perform better on different fiber amplifier models.
3. Robustness guarantee: After introducing Huber loss function and data enhancement technology, the error of parameter estimation of our algorithm is greatly reduced when the signal-to-noise ratio (SNR) is 25 dB, compared with the traditional MSE objective function. In addition, the confidence interval given by bootstrap method provides a quantitative basis for the reliability of our identification results and meets the requirements of high reliability engineering applications.

This research not only provides a new method with high precision and high robustness for intelligent modeling and parameter identification of optical fiber amplifiers, but also provides important theoretical reference and technical ideas for parameter identification and health management in other complex industrial systems (such as power electronics and precision manufacturing).

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