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ABSTRACT

Real-time current monitoring of currents in smart grid poses significant challenges, particularly within multi-conductor cables where inherent phase imbalance and complex electromagnetic coupling distort the magnetic field patterns, complicating accurate measurement. Conventional non-invasive techniques are often applied to a single conductor, insufficient adaptability to multiple varying conductor arrangements, and require operational interruption for installation. To address these issues, this study designs an angle-compensated non-invasive current measurement method for multi-conductor cables with an annular TMR sensor array. A current inversion model incorporating conductor position and inclination parameters is established. A dual-stage optimization strategy combining Particle Swarm Optimization and the Levenberg–Marquardt Algorithm is proposed to solve the inversion problem efficiently. Experimental results demonstrate that the maximum current error remains below 7% under balanced three-phase conditions. The method also maintains high accuracy in the presence of conductor eccentricity, enabling reliable non-invasive current measurement across diverse multi-conductor configurations.

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I. INTRODUCTION

Accurate current measurement is essential for monitoring and control in power systems.[1,2] The operational safety of multi-conductor cables is essential to the overall reliability of distribution networks.[3,4] Nevertheless, the composite structure of multi-conductor cables presents difficulties for conventional current measurement techniques designed for single conductor. Existing methods generally require to penetrate the cable's outer insulation for sensor installation. Such intrusions not only undermine insulation integrity and elevate safety risks, but also hinder effective smart grid monitoring.[5]

Non-invasive current measurement is crucial for smart power systems as it preserves cable integrity and offer strong environmental adaptability.[6] For single-conductor measurements, Zhang *et al.* designed a 3D TMR sensor array for eccentric or tilted conductors,[7] while Chen and Chen used a 90° phase-shifted Hall sensor configuration.[8] Despite their improved accuracy and broader applicability, these methods are unsuitable for multi-conductor systems. The magnetic fields from individual conductors couple and superimpose, and are susceptible to external stray interference, giving rise to nonlinear distortion in the measured field.[9] Furthermore, conductor displacement and tilt—often resulting from factors like mechanical vibration during installation—further exacerbate this complexity. These issues complicate accurate current inversion and impair the adaptability of measurement methods, hindering high-precision measurement in multi-conductor systems.[10]

This study develops an annular TMR sensor array for non-invasive monitoring of multi-conductor cable currents. Based on electromagnetic theory and magnetic field superposition, we establish a current-field mapping model incorporating conductor position and tilt angle. A dual-stage inversion algorithm combining Particle Swarm Optimization (PSO) and the Levenberg–Marquardt Algorithm (LMA) is then proposed to solve the resulting nonlinear equations, accurately reconstructing phase currents in three-conductor cables and providing a reliable monitoring solution.

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II. MEASURING STRUCTURE BASED ON AN ANNULA TMR ARRAY

We design an annular array of eight TMR sensors (S1–S8) positioned equidistantly along a circle of radius R. The array is mounted directly on the surface of a three-conductor cable, with each sensor aligned tangentially to the array circumference as shown in Fig. 1,

$$\begin{cases} i_1(t) = I_{1M} \sin(\omega t), \\ i_2(t) = I_{2M} \sin(\omega t + 2\pi/3), \\ i_3(t) = I_{3M} \sin(\omega t - 2\pi/3). \end{cases} \quad (1)$$

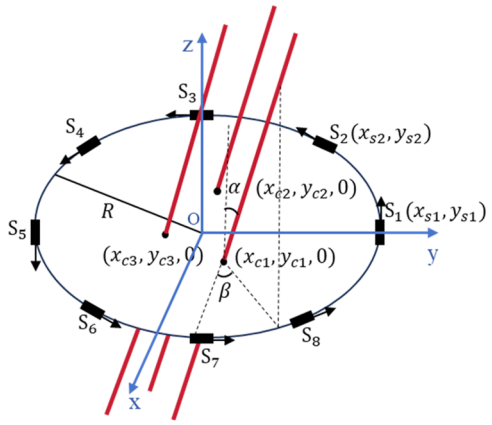


FIG. 1. Annular TMR sensor array for measuring three-conductor cable current.

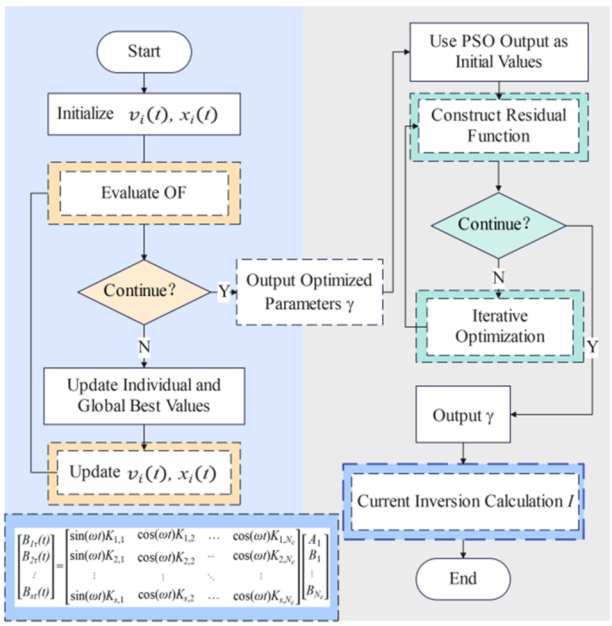


FIG. 2. Flowchart of the optimization algorithm.

The currents flowing through the conductors are denoted as $i_1(t)$, $i_2(t)$, and $i_3(t)$, while t represents the time elapsed. The direction vector of a conductor is expressed as $l = (m, n, p)$, where $m = \sin\alpha\cos\beta$, $n = \sin\alpha\sin\beta$, $p = \cos\alpha$. α: angle between the conductor and the z-axis. β: angle between the conductor's projection on the xy-plane and the x-axis. θ: angle between the sensor's sensitive axis (unit vector expressed as $(-\sin\theta, \cos\theta)$) and the x-axis.

For an infinite straight cable, the tangential magnetic field at the sensor, derived from the Biot–Savart law, is given by Eq. (2),

$$B_{\tau m}(t) = \frac{\mu_0}{2\pi} \sum_{j=1}^{3} K_j \cdot i_j(t), \quad (2)$$

where

$$K_j = \frac{p[(y_s - y_{cj})\sin\theta + (x_s - x_{cj})\cos\theta]}{p^2(y_s - y_{cj})^2 + p^2(x_s - x_{cj})^2 + [m(y_s - y_{cj}) - n(x_s - x_{cj})]^2}$$

and μ_0 denotes the permeability of free space, (x_{cj}, y_{cj}) $(j = 1, 2, 3)$ and (x_{si}, y_{si}) $(i = 1, 2, 3, 4, 5, 6, 7, 8)$ denote the position coordinates of three conductors and each magnetic field sensor.

III. THREE-PHASE CURRENT INVERSION METHOD BASED ON EVOLUTIONARY ALGORITHMS

The system of equations, based on the tangential magnetic fields from the eight TMR sensors, is established using the

TABLE I. Parameter settings of the PSO algorithm.

Parameter type	Population size	Maximum iterations	Inertia weight	Cognitive factor	Social factor
Parameter value	32	200	0.9 → 0.4	2.0	2.0

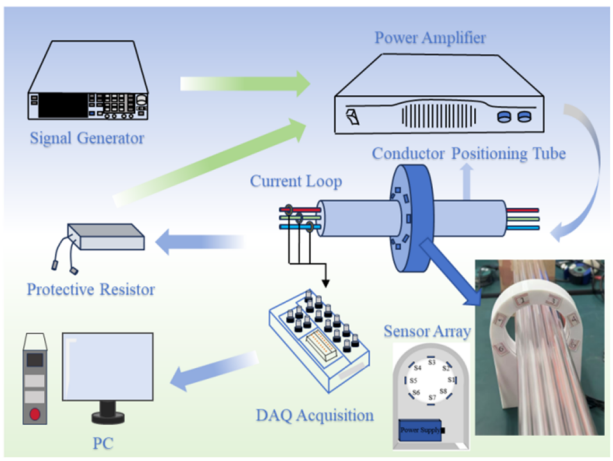


FIG. 3. The multi-conductor current measurement experimental setup.

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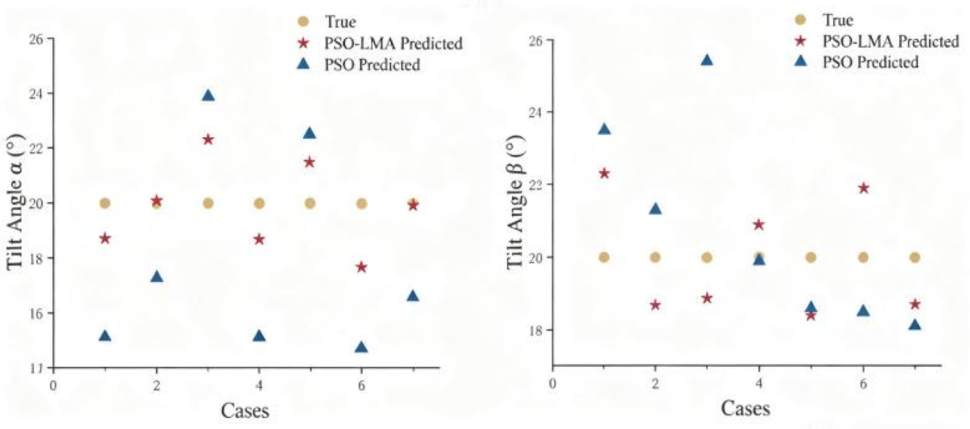


FIG. 4. Comparison of measurement results for conductor spatial distributions.

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superposition theorem. Following this, the discrepancy between the theoretical and measured magnetic field values at the eight sensor locations is regarded as an objective function (OF):

$$\min\left[\mathrm{MSE}(\gamma)\right] = \min\left\{\frac{1}{8}\sum_{i=1}^{8}\left[V_{i,sim(\gamma)} - V_{i,obs}\right]^2\right\}, \tag{3}$$

where $\gamma = [\alpha\ \beta\ x_{c1}\ y_{c1}\ x_{c2}\ y_{c2}\ x_{c3}\ y_{c3}]$ represents the parameter vector to be optimized, $V_{i,sim(\gamma)}$ denotes the theoretically calculated magnetic field value, and $V_{i,obs}$ stands for the actual measured magnetic field value.

The conductor orientation estimation is a multi-variable nonlinear optimization. We propose a dual-stage strategy that hybridizes the global search of PSO with the rapid local convergence of LMA. This hybrid approach ensures robustness to initial values and a good trade-off between global exploration and local refinement. The flowchart of this strategy is illustrated in Fig. 2. To ensure the effectiveness of the global search in the first stage, the key parameters of the PSO algorithm are configured as listed in Table I. The inertia weight decreases linearly from 0.9 to 0.4 to balance exploration and exploitation.

As a core component of an annular uniaxial magnetic sensor array, this method handles complex multi-conductor scenarios with variable layouts by integrating spatial positions and tilt angles into the inversion model. This enables a nonlinear optimization tightly coupled with angle compensation, allowing the system to adapt to layout variations and tilting.

Following the PSO phase, the LMA performs local refinement until the maximum iteration is reached, obtaining the conductor spatial parameters.

For N_c conductors, by substituting the time-varying currents into the Biot-Savart law, the total magnetic field measured by each sensor can be expressed as

$$B_{s\tau}(t) = \sum_{j=1}^{N_c}\left[K_{s,j}\ \sin(\omega t)A_j + K_{s,j}\ \cos(\omega t)B_j\right], \tag{4}$$

where $K_{s,j} = \mu_0\ \cos\ \theta_{s,j}/2\pi r_{s,j}$ denotes the response weight of the s-th sensor to the current in the j-th conductor; $r_{s,j}$ denotes the perpendicular distance from the s-th sensor to the j-th conductor; $\theta_{s,j}$ represents the angle between the sensitive direction of the s-th sensor and the magnetic field generated by the j-th conductor.

Once the spatial directions of conductors are determined, the coefficient matrix is defined, and the currents can be directly computed using Eq. (4).

IV. EXPERIMENTS AND RESULTS

Figure 3 illustrates the experimental setup for multi-conductor current measurement using the proposed annular TMR sensor array. The system includes an eight-sensor TMR2602 array, three signal generators and power amplifiers, three current sensors, data acquisition cards, and a controller.

A 40-mm-radius sensor array housing was 3D-printed. An acrylic fixture secured the conductors' spatial distribution and their positions relative to the array. Currents in the three loops were measured simultaneously as inversion references. Sensor signals were acquired by an NI BNC-2110 unit.

Under a balanced three-phase current condition with each phase maintained at 5 A, the fundamental components were extracted from the acquired signals and fed into the inversion algorithm. A comparison of the conductor spatial positions calculated by the PSO-LMA and PSO algorithms against the actual positions under different layout scenarios is presented in Fig. 4.

Figure 4 compares the PSO-LMA and PSO algorithms for optimizing conductor spatial parameters. PSO-LMA shows superior accuracy to the PSO algorithm across all scenarios, with estimated values exhibiting closer clustering around true positions and tilt angles, thereby providing a reliable basis for current inversion. In contrast, PSO results display notable dispersion and deviation, as its tendency to converge to local optima is effectively avoided by the hybrid PSO-LMA strategy. In the subsequent current inversion, the reconstructed conductor geometry is employed in Eq. (4) to determine the three-phase current amplitudes. The maximum relative error in the fundamental current amplitudes is 1.2% as evidenced in Case 2. In contrast, when the conductors are in the same position but without tilt angle compensation, the error of current reaches 6.03%.

Figure 5 shows the errors in the reconstructed fundamental current amplitudes under different conductor positions, with the actual current amplitudes held constant. When conductors are near the sensor array's edge (Cases 3 and 5), the magnetic field's steep spatial gradient weakens the signal and lowers the signal-to-noise ratio at distant sensors, which ill-conditions the inverse problem and increases the algorithm's sensitivity to errors, thereby degrading precision. In contrast, central conductor concentration yields a more uniform and linear field, enabling higher algorithmic accuracy, as seen in other cases.

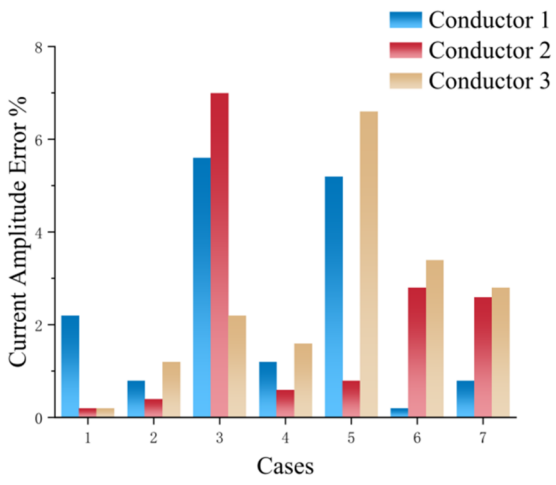


FIG. 5. Measurement errors of current amplitude.

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V. CONCLUSION

This study designs an effective non-invasive method for precise current inversion in multi-conductor cables using an annular TMR sensor array and a hybrid dual-stage optimization strategy. The key findings are

(1) The proposed PSO-LMA algorithm demonstrates high reliability in initial value selection, achieves more accurate optimization results than the single PSO algorithm, and excellent measurement accuracy in solving the complex nonlinear inversion problem.
(2) Experimental results show that the maximum relative error in current measurement remains within 7%, even the most challenging cases where the conductors are located near the edge.
(3) For Case 7 where the conductors are located around the center, the angle compensation reduces the current inversion error from 6.03% without compensation to 1.2% with compensation, significantly enhancing reconstruction accuracy. This optimization performance is largely attributed to the angle compensation mechanism, which mitigates magnetic field distortion induced by conductor tilt.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Fugui Liu: Conceptualization (equal); Supervision (equal); Writing – review & editing (equal). **Shuai Zhao**: Data curation (equal); Methodology (equal); Writing – original draft (equal). **Shuokao Mu**: Data curation (equal); Methodology (equal); Validation (equal). **Yongjian Li**: Funding acquisition (equal); Writing – review & editing (equal). **Changgeng Zhang**: Funding acquisition (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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