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A Review on Computational Heuristics in Harmonics Estimation: History, Current topnotch, Challenges and Future Prospects

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ABSTRACT

Harmonics estimation plays a crucial part in reducing or eliminating harmonic aberrations in power systems. The ability to perform harmonic elimination needs effective estimation of exact harmonics that is present in a system. Metaheuristic methods for harmonics estimation are creative ways to handle complicated signal analysis. In order to identify harmonic components in electrical signals, these techniques make use of the power of optimization algorithms. Researchers want to improve harmonics estimation's accuracy and effectiveness by utilizing metaheuristic methods, leading to cleaner and more dependable power systems. Offering potential methods for the reduction of harmonic distortions in contemporary electrical systems, this cutting-edge field is still developing. The essential component of feature extraction, which significantly improves the harmonics mitigation efficacy approach, is important to the optimization process. This inquiry includes a thorough analysis of several relevant literature sources as well as an overall evaluation. It employs a variety of methodologies to identify fundamental frequencies and harmonics in the time, space, and frequency domain. Additionally, during the course of this investigation, the integration of signal processing with Meta-Heuristic approaches is examined and evaluated. This investigation provides a thorough overview of modern methods for fundamental frequency and harmonic extraction, together with a thorough analysis and characterization of their benefits and curbs.

Keywords: Parameter estimation; harmonics; Meta-Heuristics optimization; swarm intelligence; artificial intelligence; power quality; electrical systems.

1. INTRODUCTION

In order to minimize negative impacts on equipment and network performance and to ensure dependable operation, harmonics estimate is essential in power systems. Nevertheless, recognizing harmonic components reliably and effectively in a variety of system configurations and operating environments presents difficulties for current methods, such as computational heuristics. To overcome these obstacles and promote the development of cleaner and more dependable power systems, it is thus necessary to improve the effectiveness and application of computational heuristics in harmonic estimation.

Power electronic equipment has become a vital part of electrical systems in the modern period, including automated protection mechanisms, intelligent computer systems, variable resistance speed drives, and more. The quality of the voltage and current waveforms must be smooth for these devices to operate at their best. Only by successfully lowering the harmonic content of input voltages and current waveforms would this be possible. [1-5]. Frequent approaches have been used in research to investigate periodic signals polluted by harmonics and sub-harmonics. The examination of harmonics distortion has drawn a lot of attention from several angles [6-15]. Numerous methods for evaluating power signals have been proposed by the research community, and various academic publications with a focus on the evaluation of harmonic contamination have been published in the literature. [16-19].

A thorough examination of harmonic stability in upcoming power systems based on electronic technology is presented in a study that starts by elaborating on the fundamental idea and phenomena of harmonic stability. It is noted that harmonic stability, which exhibits waveform distortions at frequencies above and below the system's fundamental frequency, is a subset of small-signal stability issues [20]. The goal of the research project presented in [21] is to calculate the relationship between the rise in temperature in transformers and the increased winding losses brought on by harmonics. The inquiry was carried out to undertake a comprehensive examination of the literature on projected possible issues related to high penetration levels and grid-tied photovoltaic islanding avoidance techniques [22]. Several factors have been outlined in a document to ensure that distributed generation won't compromise the power quality, safety, or dependability of the distribution

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system. While some of the challenges highlighted are similar to low voltage distribution networks, the focus of this article was on radial systems [23].

A number of factors that contribute to voltage imbalance in industrial settings and on the power system are discussed in [24], along with the detrimental consequences that these factors have on the system and its components, including drives, power electronic converters, and induction motors. A comprehensive and methodical review of the research, advancements, evaluation methods, and enhancement technologies related to hosting capacity limits is given in a study. The findings from worldwide experience and measurement campaigns on power quality evaluations and the analysis of grid stability of electric networks with significant penetration of solar generation are presented in a study [25]. The findings of a study on measurement campaigns and worldwide experience with power quality studies and grid stability assessments of electric networks with significant photovoltaic (PV) generating penetration are presented in [26]. The primary goal of [27] is to examine the network interactions of various inverter topologies and control choices, as well as to investigate the phenomenon of harmonic interference of huge populations of these inverters. Advanced power electronic interfaces, according to [28], will enable distributed energy (DE) systems to lower overall interconnection costs while increasing practicality through enhanced voltage/volt-ampere reactive (VAR) support and power quality, increased system stability through a reduction in error contributions, and adaptability while working with different DE sources.

An investigation is conducted into the harmonic stability resulting from the interplay between the passive elements and power converters wideband control in an electronic power system using alternating current [29]. Two novel metrics are suggested in a work to identify the islanding operation of voltage imbalance in distributed generation and total harmonic distortion of current. In order to identify the islanding circumstances, the suggested technique successfully blends the previously suggested parameters with the recently proposed parameters [30]. To calculate and measure the components harmonic emissions of renewable energy sources, an analytical method was created. Using algebraic modeling language, the suggested problem of AC mixed integer nonlinear optimization was fixed. The 48-bus power system in Nigeria and the undistorted Garver test bus infrastructure is used to illustrate the suggested paradigm [31]. The current status of battery charger harmonics is summarized.

Analysis is done on how harmonic distortion affects the distribution system, particularly the distribution transformers [32]. A study addresses a number of system problems that might arise when distributed resources (DR) are incorporated into distribution networks. The effect on system voltage, the relationship between DR and capacitor operations, and the relationship between DR and voltage regulator operations are the voltage concerns that are discussed [33]. The result of the suggested solution, DC link capacitors, is an economical method of reducing DC-harmonics that allows designers to create systems with many inverters in practice even in situations where the majority of drives are not running at their rated power outputs [34]. The example model with an inclusion between the electrodes provided by DC voltages with selected harmonics is used for the investigations. At a fixed DC level, two scenarios were examined: one with a changeable AC amplitude and the other with a changeable AC source frequency that was tuned to the harmonics of 50, 150, 300, and 350 Hz [35]. In order to compensate for VAR and filter out complex harmonics produced by arc and ladle furnaces, the article describes way for choosing components of a type C filters that works with traditional type LC filter. In a steel factory that was fed with 110 kV system, increased nonlinear loads and harmonic currents were recorded as part of the study [36].

Recent updates to the real-time simulator, which is a free source DP sim, are described in an effort to handle more significant use cases involving power electronics linked to the power grid and expanding grid sizes [37]. In order to provide a range of grid ancillary services, the vector control implementation of a grid-tied inverter in the d q reference frame is given utilizing the electric vehicle grid integration (EVGI) system in a study that develops a large-scale EVGI system [38]. A novel approach utilizing a predictive model-based adaptive filter to lower the overall harmonic distortion (THD) of PV systems is presented in a study. At the later stage of the PV system, a single-step procedure was used rather than lowering the generated THD at each stage [39]. On the EV's high-voltage DC bus, notable current harmonic disturbances between 50 Hz and 4 kHz have been seen from real-world observations. Studies on the effects of these harmonics on battery system deterioration have been carried out in the little literature [40]. A study presents a robust variable structure control for a three-phase grid-connected inverter with an LCL filter. In addition to the advantages of the control sliding mode, one of the power converters' well-established control strategies, the suggested control plan includes a unique partial states observer using the immersion and invariance approach, which is suitable for this application due to its intrinsic robustness and speed of convergence [41]. The study conducted in reference [42] centers on precisely estimating power system harmonics through the utilization of a hybrid multiverse optimizer architecture using weighted least squares.

A fresh framework and management mechanism for versatile DVRs for voltage quality adjustment is created and modeled in [43]. Proportional and sequence decouple resonant controllers were combined to provide the novel control scheme in the stationary frame. An extensive analysis of the several dynamic modeling approaches for the system for transmitting high voltage direct current (HVDC) is presented in a study. Accordingly, a thorough analysis of several HVDC mathematical models, such as average value modeling, voltage source converters, and line commutated converters, is conducted [44]. Without attempting to solve laborious non-linear transcendental formulas, a novel way of mitigation of low order harmonics in modification of fundamental switching frequency is presented in the [45] study for high-power solar applications. The effects of various distribution transformers equipped with electric vehicle chargers and distribution networks' voltage quality are evaluated and mitigated in this article. To precisely evaluate the effects of EV harmonic currents on aging and losses interface transformer, the weighted arithmetic mean is applied to account for the EV battery's charge level [46].

1.1 Overview of Harmonics in Power Systems

In alternating current, harmonics in power systems are non-sinusoidal electrical waveforms that appear at frequencies that are integer multiple of the fundamental frequency, as shown in Figure 1.

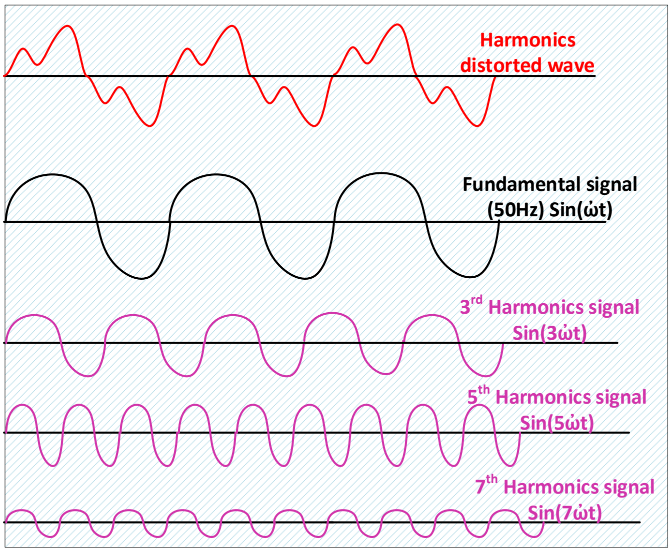

Fig. 1 Harmonics distorted waveform

Because they have the potential to have a wide range of negative impacts on electrical systems, equipment, and overall power quality, harmonic distortions in power systems are extremely important. They can originate from a number of things, such as power electrical equipment and nonlinear loads like computers and variable speed drives. In power systems, harmonics disrupt the typical sinusoidal voltage and current waveforms. Since the outset, research has been conducted to reduce power system harmonics and provide customers with dependable, clean fundamental frequency sinusoidal electricity that will not destroy their equipment. Some consequences of harmonics in power systems are reflected in Figure 2.

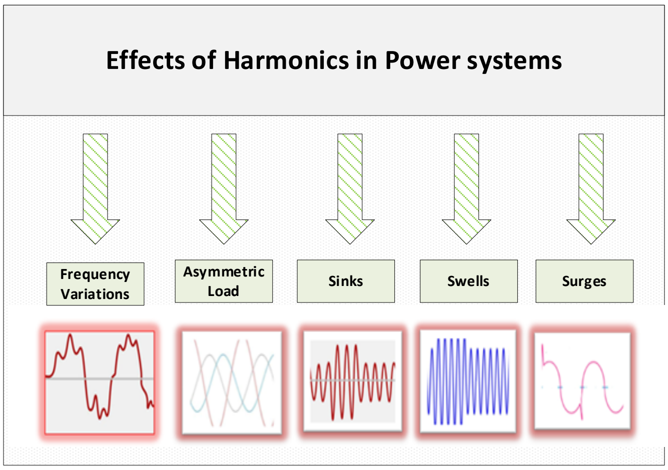

Fig. 2 Adverse impact of harmonics in power systems.

Here are a few main arguments for why harmonic distortions should be taken into account:

- Electronic devices and equipment that are sensitive to harmonics may malfunction. They cause operational mistakes and downtime by interfering with the operation of computers, control systems, and other equipment;
- Power distribution systems have higher losses because of harmonics. This lowers energy efficiency, which increases energy expenses and consumption. This is particularly important in commercial and industrial settings;
- Electrical components experience thermal stress from harmonics, which can result in overheating. Extended exposure to harmonics can reduce the lifespan of conductors, capacitors, and transformers, requiring more frequent replacement and maintenance;
- The voltage and current waveforms are distorted by harmonics, which lowers electrical power quality. Voltage flicker may come from this, irritating customers and prompt complaints. Defective power quality can also affect how delicate gadgets and equipment function;
- Electromagnetic interference caused by harmonics can interfere with other electrical equipment's regular operations. Communication networks, sensitive equipment, and the reception of radio and television signals can all be impacted by this interference;
- Harmonics have the potential to cause safety equipment, such as circuit breakers, to trip inconveniently. Safety issues and service disruptions may arise from this;
- Standards and laws in several countries regulate harmonic levels in power systems. Utilities and businesses must adhere to these requirements in order to provide a steady and secure electricity supply. There may be penalties and legal repercussions for non-compliance;
- In order to maintain environmental sustainability, harmonics management is crucial since reduced energy efficiency brought on by harmonics can result in higher energy usage and emissions of greenhouse gases.

The significance of harmonic distortions arises from their ability to impair power quality, interact with other electronic devices, shorten equipment lifespans, reduce energy efficiency, and disturb electrical system functioning. In order to comply with regulations, minimize environmental effects, and ensure a dependable and efficient electrical supply, harmonic management is crucial.

1.2 Historical Prospective of Harmonics Estimation

A historical view on harmonics estimates in power systems sheds light on how analytical and quantitative harmonic analysis and quantification methodologies have changed throughout time.

1.2.1 Early approaches for harmonics estimation

A multiphase model, synchronized measurements, voltage and current waveform measurements, and a multi-frequency model, that is, a technique that takes waveform distortion or harmonics into account, are the foundations of a power system state estimation described in [47]. Based on the "subspace" approaches, a novel approach to harmonic and inter-harmonic investigation is presented. The methodology for measuring each harmonic source's harmonic contribution to system voltage distortion is covered in this publication [48]. To mitigate and regulate system harmonic levels, determining each harmonic source's harmonic contribution is crucial. For harmonic sources, the idea of voltage superposition with equivalent voltage models may be applied to assess harmonic contributions. In [49], a modified Fourier analysis-based harmonic current calculation approach that is appropriate for active power filters with DSPs is designed and implemented. For real-time applications, the suggested method works well for controlling and monitoring load current harmonics. The study examines the choice of mother wavelet, sampling frequency, and frequency properties of the two most often used wavelet filter banks in harmonic investigation. It also evaluates how well the suggested approach performs in comparison to outcomes from the study of discrete Fourier transform and the International Electrotechnical Commission's harmonic group concept under various measurement scenarios [50]. Due to its remarkable applicability across nearly all domains, the Fourier discrete chirp transform is particularly useful for matching the numerous frequencies of a steady signal that has many harmonics [51]. An increasingly significant concern in the evaluation of power worth is the calculation of effective harmonics for electrical signal measurement. The methodology for measuring each harmonic source's harmonic contribution to system voltage distortion is covered in this publication [52].

To mitigate and regulate system harmonic levels, determining each harmonic source's harmonic contribution is crucial. The idea of voltage superposition for harmonic sources using equivalent voltage models may be used to assess harmonic contributions. Because of its high computing efficiency, FFT, or the fast Fourier transform, has been used extensively in signal processing. In order to continuously measure inter harmonics and harmonics of the electricity system, an FFT method that is directly applied while maintaining a constant sample rate may produce adrift results because of the ghostly leaking and the picket fence impacts related to the fundamental frequency change of the system and a poorly chosen sample time frame [53]. In [54], an innovative processing desynchronize method for the study of harmonic and interharmonic is introduced. Its outcomes are completely compliant with the IEC standard and it possesses broad validity. An array of traditional and sophisticated Fourier techniques is described, which are helpful in the analysis of very long-duration astrophysical time series in which the temporal resolution of the individual data points is substantially less than the observation period [55]. Presented a new depiction of cortical surfaces using weighted Fourier series (WFS). The explicit smooth functional estimate of an unknown cortical border as a linear blend of basic functions is provided by WFS representation, a data smoothing approach [56]. Discrete Fourier transform (DFT) is a popular technique for filters that may remove harmonics easily with basic computation. Nevertheless, throughout the fault interval, there are significant harmonics and offsets in the measurements of voltage and current. The accuracy and rate of convergence of the DFT's fundamental frequency signal are significantly impacted by the DC offset. The authors of this study provide a unique Fourier technique for eliminating DC offset in a voltage or current signal [57]. Image representation at the gray level of the Fourier Mellin transform capability for pattern detection, retrieving images from databases, and reconstructing for harmonic visibility is discussed in a work [58]. A thorough examination of discrete Fourier transform error is provided in [59], along with explanations of why synchronous sampling ensures accuracy and how non-synchronization of sampling frequency with signal frequency increases error.

An inter-harmonics estimation approach based on the interpolation FFT algorithm is suggested to increase the measurement accuracy of inter-harmonics in electric power systems and to minimize mistakes caused by employing a quick Fourier transform for a study of an unsynchronized sample sequence [60]. Various techniques are employed in [61] for PV inverter continuous grid monitoring. The PV inverter may assess the grid impedance directly by introducing an unusual harmonic current and monitoring the grid voltage response, resulting in a quick and affordable deployment. This article describes a three-phase uncontrolled rectification charger that uses a passive power factor correction connection along with the principles of operation for the charging current in modes that are both continuous and discontinuous, which are dependent on the charging power [62]. The PV inverter's digital implementation with several sophisticated, reliable techniques and online integrated methodology to calculate the impedance of the utility grid is described in the work [63]. In [64] an approach for identifying fundamental frequency and harmonic components is offered for aircraft electrical systems. The goal of [65] is to describe distinct characteristics of power quality techniques and events for obtaining them from waves of voltage and/or current that have been recorded by using wavelet and Fourier transforms. A study describes how to use the wavelet packet transform to calculate the harmonic groups present in waveforms of voltage and current. In order to achieve production bands consistent using the harmonic groupings established while measuring harmonics standards for systems that use power supplies, the wavelet packet decomposition technique is chosen [66]. New digital instruments, such as harmonic analyzers and power quality indicators, are created in paper [67]. An improved method for measuring the voltage and current of the power system harmonics is conferred in this study [68]. It can estimate harmonics in waveforms with time-varying amplitudes as well as stationary waveforms. In [69], a measurement-based approach for determining the model parameters is established and is appropriate for application in frequency-domain harmonic analysis of home appliances. The form and frequency range of the harmonic current spectrum, the harmonics fluctuation with the wind turbine operating point, the statistical properties of their magnitude and phase angle, the impact of grouping and time-averaging, and the features of their symmetrical components are among the specific issues covered [70].

The technique for determining the utility harmonic impedance and the harmonic voltage emission level at the point of common coupling (PCC) is presented in research [71]. The covariance characteristic of random vectors can be used to remove the variable item of the background harmonic in the deviation formulation, as harmonic current at the PCC typically shows low reliance on the utility side background harmonic. A study [72] looks at various topologies from the perspectives of operational losses, fault tolerance, modularity, complexity, multi-terminal operation, power semiconductor needs, and reactive component requirements. To do engineering trade-off studies, wind energy/bulk transmission developers may employ detailed analytical models and a benchmark application to generate a comparative evaluation of the options. The techniques successfully address the difficulties in rotor position estimate at first and are also appropriate for sensor-less beginning that is dependable when there is little load [73]. In [74], analytical formulas are obtained that ascertain the inaccuracy in the phase angle measured by phase-locked loops in the presence of grid voltage harmonics and imbalance. This work [75] creates a model that links the harmonic content of the input current to actual power usage for variable electronic loads, particularly for loads that have actively regulated inverters powered by uncontrolled utility rectification. To get the best estimation of the power system harmonic content, a Kalman filter is employed. Gaussian noise is added to the power system voltage and line flows at various harmonics that are derived from a harmonic load flow program in order to imitate the observations [76]. The model presented in the [77] article is based on information gathered from many prior thematic and statistical research as well as from an investigation of a selection of industrial companies that is representative.

Power electronic Grid-Connected Converters are extensively used in renewable energy sources as grid interfaces. In this study [78], a space vector modulation approach for extended direct power control with better operating performance under grid distortions is proposed. An evaluation is conducted on the discrete Fourier transform (DFT) approach at three levels by means of computer-simulated signals that have inter-harmonics and harmonics. A real-time digital simulator is used to assess the performance of the hardware prototype that employs the DFT three-level approach, which is likewise based on an electronic signal processor. The evaluation's findings demonstrate that the three-level DFT approach can accurately estimate power system frequency in real time [79]. It is suggested to use a cross-feedback network with various adaptive vector filters for a model-based position observer in order to reduce the position estimation error with harmonic fluctuations for position sensor less internal permanent magnet synchronous motor drives [80]. The advantages of controlled induction motor drives are their great dependability and inexpensive cost as compared to motor shaft-mounted mechanical speed sensors. In order to change the sensor, measured voltages and currents in the stator at the terminals of the motor are used to get information about the rotor speed [81].

In this study [82], a thorough experimental method for determining the magnetic model of all types of synchronous electrical devices is proposed and formalized. This study [83] looks into 3D object retrieval, using a polygonal mesh as a query to return comparable things from a set of 3D objects. The initial phase in the algorithmic process is normalization when models are converted into canonical coordinates. The advantages of controlled induction motor drives are their great dependability and inexpensive cost as compared to motor shaft-mounted mechanical speed sensors. The recorded stator voltages and currents at the motor terminals are used to derive the rotor speed information in order to replace the sensor [84]. In order to account for harmonics and the reactive power needed for nonlinear loads, a 3-phase shunt active power filter has been thoroughly designed, simulated, and experimentally investigated in this article [85]. A new control strategy is put out for the dynamic voltage restorer in an effort to provide quick reaction times and efficient sag correction. The estimated phasor parameters are significantly less affected by noise, harmonics, and disturbances thanks to the used least error squares calculated filters [86]. Using a decomposition on a collection of orthogonal vector spherical harmonics, comparison of star catalogs with position and proper motion components is performed. The independence of the decomposition from an earlier model and the invariance qualities of this method yield both theoretical and practical advantages [87]. A speed and position estimate technique that is computationally efficient and can be used for AC motor drives in general is proposed [88]. To estimate the fundamental frequency of asynchronously sampled signals in power systems, a two-stage approach is developed. The electrical signal is reconstructed at a new sample time using time domain interpolation. The reconstructed signal is then, in order to eliminate harmonics, passed via a tuned sine filter [89]. The estimate of magnet polarity in permanent-magnet synchronous machines is examined in this work. The robustness of the magnet polarity estimate is affected by extra signal content since the magnet polarity is inferred from signals with a low signal-to-noise ratio [90]. A reliable control strategy for the current of a permanent magnet synchronous motor using a fundamental adaptive disturbance observer is shown in this study [91]. A harmonic reduction technique for a distorted distribution system is presented in this study [92] is expected that a grid with high-order current harmonics exists in order to assess the suggested approach. Due to the pulse modulation of an active filter, which is made up of a buck-boost converter coupled back-to-back to a polarity-flipping inverter, current distortion can be reduced. In real life, this system would be a renewable energy source's power electronic interface; as such, it converts a harmonic source into a damping harmonics system. Examining the boundedness issue for maximal operators, linked harmonics analysis was linked to averages along finite-type smooth hypersurfaces S in three-dimensional Euclidean space [93]. In order to enhance the low-voltage ride-through capabilities for full-scale permanent magnet synchronous generator wind power systems, a new fault detection technique and inverter management scheme are presented in a study. The wind power systems can maintain a safe DC-link voltage range with the use of fast fault detection. Online adaptive parameter estimate serves as the foundation for the suggested fault detection technique [94].

There are several methods for estimating harmonics in signal processing, which may be broadly divided into two groups: parametric and nonparametric approaches. Depending on the approach taken, the estimated signal may be time-independent or dependent. Various approaches and procedures for power systems and signal processing harmonic estimation. These methods may be roughly divided into several kinds, however they range in terms of applicability and complexity. Here are a few popular methods for estimating harmonics:

a.Fast Fourier Transform;

For signal processing, including the estimate of harmonic components, Fast Fourier Transform is a popular tool, a fast technique for calculating the Discrete Fourier Transform [60]. A discrete signal is represented by a series of complex integers, which the DFT converts into its frequency domain representation.

$$y[t] = \sum_{n=0}^{N-1} z[x] e^{\frac{-i2\pi}{N} t_n} \quad , \tag{1}$$

here y[t] is the complex DFT output at frequency index t.

y[t] is input, *N* is length of input signal and *I* is imaginary unit.

By taking advantage of the computation's symmetries and redundancies, the Fast Fourier Transform method effectively computes the DFT while using fewer arithmetic operations. Implementing the FFT via the Cooley-Tukey radix-2 algorithm is a popular technique.

b.Wavelet transform;

Any signal may be broken down using wavelets using the wavelet transform to provide a thorough analysis with numerous time-frequency resolutions [144].

By comparing the signal with the proper wavelet over a predetermined time period, this approach yields a coefficient that may be thought of as a signal-wavelet correlation. To achieve discrete levels of decomposition in Discrete WT (DWT), the translation and dilation parameters are maintained as functions of an integer parameter m.

Consider a discrete signal y[t] defined as;

$$Y_w(a,k) = \sum_{n=0}^{N-1} y[n] \frac{1}{\sqrt{q_o^{z-1}}} \partial\left(\frac{n - k_o q_o^{z-1}}{q_o^{z-1}}\right) \quad , \tag{2}$$

where k is the index of coefficient at ath level, a gives dilation and k gives translation parameter.

c.Discrete wavelet transform;

A mathematical technique for signal processing, including signal analysis and estimation, is the discrete wavelet transform [150]. It breaks down a signal into a collection of wavelet functions so that frequency and temporal information may be recorded.

Let y[t] is the discrete signal of length N, and consider a one dimensional DWT with a signal level of decomposition. The DWT decomposes the signal into approximation coefficient (P) and detail coefficient (D);

$$P[i,j] = \sum_{n} h[n.]\ \ y[2j-n.]\ , \tag{3}$$

$$D[i,j] = \sum_{n} g[n.]\ \ y[2j-n.]. \tag{4}$$

In the above equation $P[i,j]$ represents the approximation coefficient,

$D[i,j]$represents the detail coefficient.

$h[n.]$，$g[.n]$are coefficients of scaling.

d.Least square harmonics estimation;

By reducing the sum of squared errors between the real signal and the model that represents the harmonic components, a technique known as least squares harmonics estimation, or LSHE, is used to estimate the parameters of harmonic components in a signal [6]. Accurately detecting the amplitude, frequency, and phase of individual harmonics in a signal is made possible by this approach.

Considering the signal y[t] that can be represented as the sum of N harmonic components.

$$y[t] = \sum_{n=1}^{N} B_i \cos(2\pi f_i(t) + \theta_i) + \varepsilon(t)\ , \tag{5}$$

where;

B_i is the amplitude of i_{th} harmonic.

f_i is the frequency of i_{th} harmonics, θ_i is the phase and $\varepsilon(t)$ represents the noise.

The objective of LSHE is to estimate the parameters B_i , f_i and θ_i for each harmonic by minimizing the sum of squared errors:

$$L = \sum_{n=1}^{K} \left| u(t_n) - B_i \cos(2\pi f_i t_n + \theta_i) \right|^2\ , \tag{6}$$

where t_n are the time instances at which the signal is sampled and K is the number of samples.

e.Prony's method;

A model-based technique for estimating sinusoidal signal parameters in a time-domain signal is Prony's method [179]. In the area of signal processing, harmonic analysis and estimation are frequently performed using this technique. Prony's method's core idea is to estimate the parameters of these sinusoids from the provided signal by modeling it as the sum of damped sinusoids.

Considering a signal y[t] that can be represented as a sum of N damped sinusoids.

$$y[t] = \sum_{n=1}^{K} B_i \cos(2\pi f_i t_n + \theta_i) e^{-\sigma_{it}}\ \ , \tag{7}$$

where;

B_i is the amplitude, f_i is frequency, θ_i is the phase and σ_{it} is the damping factor.

The prony's method involves fitting the given signal to this model and solving for the parameters. To estimate the parameters, Prony's method typically involves constructing a Toeplitz matrix T and solving the linear system of equation:

$$T_a = -r\ , \tag{8}$$

here a is the vector of coefficient, r is the vector of the first column of the Toeptitz matrix.

When the signal-to-noise ratio is high and the number of sinusoids in the signal is either known or can be accurately predicted, Prony's approach works well. Nonetheless, noise sensitivity may exist, and noise or imprecise quantification of the number of sinusoids may impact the precision of the parameter estimate. In actual use, Prony's method may be combined with other signal processing methods; however, the particular needs of the application and the properties of the signal should be carefully considered.

1.2.2. Evolution of Harmonics Estimation Techniques

The increasing complexity of power networks and technical improvements have led to notable progress in the evolution of harmonics estimate approaches. These methods are now more precise, effective, and flexible to various power quality problems.

The development of harmonics estimates approaches reflects the ongoing modification of procedures and equipment to satisfy changing power system requirements. To solve harmonics issues in power systems, modern computational techniques, including artificial intelligence and machine learning, are combined with more conventional methods. These methods are now more precise, quick, and flexible for handling intricate and changing power quality problems. Some possible solutions of harmonics estimation techniques are shown in Figure 3.

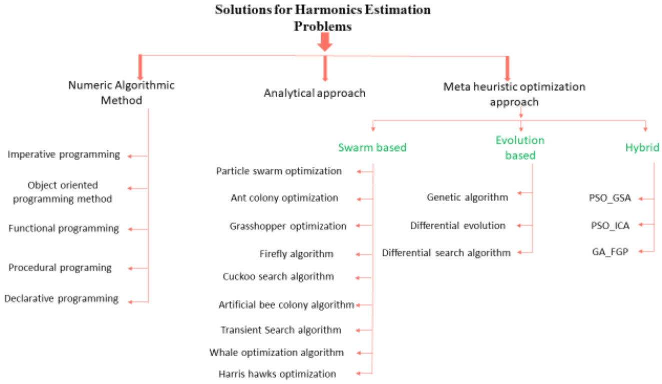

Fig. 3 Possible solutions for harmonics estimation problems.

An Evolutionary Operators Equipped Grey Wolf Optimizer is suggested by Saxena et al. in 2020. In this suggestion, a sinusoidal function enabled bridging is suggested, and during the position updating phase, a tournament selection operator, crossover, and mutation operation are also added. [95]. A quick estimate of all harmonic components of arbitrarily distorted single-phase signals, such as voltages or currents in power systems, is proposed using (mSOGIs), modified second order generalized integrators. Based on the internal model idea, the estimate produces an overall observer made up of parallelized mSOGIs [96]. Using optimization models, a research proposes a unique static harmonic state estimate approach for power distribution networks, assuming a sparse distribution of synchronized phasor measurement units throughout the feeders. To determine daily load profiles and harmonic components from dominating sources, optimization problems are specifically developed for each harmonic order to be examined at regular intervals [97]. For increased efficacy in the identification of the harmonics, inter-harmonics, and sub-harmonics parameters in power quality assessment, an effective analysis explains how filter banks are connected to ESPRIT (FB-ESPRIT). FB-ESPRIT initially processes the signal via an analysis filter bank with parameter L before applying ESPRIT to each of the L resulting signal sub-bands independently while the signal is spread throughout its whole bandwidth [98]. Four Kalman-filter-based algorithms, the extended Kalman filter, the unscented Kalman filter, the cubature Kalman filter, and the ensemble Kalman filter, were proposed by Liu, Hui, et al. in a study [99]. The impact of white noise on amplitude and phase estimates produced by frequency shifting and filtering based on discrete Fourier transform is examined in [100] article. By considering the two processed samples overlapped, the amplitude and phase variance expressions based on filtering and frequency shifting are theoretically generated using the benefits of the Equivalent Weighting Filter, comparable noise bandwidth, and correlation overlap. Whether or not the conventional assumptions hold true, the utility harmonic impedance may be precisely determined by choosing the self-correlation of the utility harmonic current source to be smaller than a tiny threshold. A modest sample size is all that is needed for the suggested technique [101].

The many methods of evaluating harmonics in electrical power networks using artificial intelligence are examined. The classification tasks of harmonic sources and harmonic source resolution of contributions. Considerations include distributed generation hosting capacity, filter-based harmonic removal, and harmonic data clustering by Ahmadreza Eslami et al. [102]. For the detection of inter, sub, and power harmonics, a smart harmonic estimator built on a better crow search method is suggested. The Augmented Crow Search Algorithm is the algorithm's name [103]. This study [104] examines and contrasts the usage of three artificial intelligence techniques for estimating harmonic parameters in power signals: Adaline, Adaline-Least Squares LS, and Particle Swarm Optimization LS. To determine how to control the PI and choose the proper PWM frequency to activate bridge rectifiers and choose the best compensation current to make up for the current loss on the power supply, a study in [105] classifies data based on the operation mode of metaheuristic optimization methods. This results in a total harmonic distortion value that is less than 5%. An Improved Squirrel Search Algorithm has been presented in [106] to improve the precision and convergence speed of the traditional approaches utilized. A sophisticated modulation method is suggested to mitigate the voltage ripples in the dc-link. The study looks at weighted total harmonic distortion and important indexes of low-order harmonic components [107]. The authors of this research developed a novel hybrid framework for least squares and particle swarm optimization that draws inspiration from quantum mechanics and is intended for real-time harmonic estimation in time-varying noisy power data [108].

The study [109] looks at several mathematical models based on regression to calibrate the Hall sensor for detecting the fundamental frequency and RMS. The study presents the findings of an experimental assessment of power quality in indoor lighting systems. The effect behavior of various lights and the technologies employed in luminaries are highlighted by an analysis of the harmonic absorptions of various types of luminaries [110]. In the scout bee phase, a novel version of the Artificial Bee Colony algorithm uses an updating equation based on the Laplacian factor. The suggested approach is first evaluated on a number of common benchmark problems in order to demonstrate the significance of the adjustment, and it is then applied to an estimator design issue [111]. A study [112] demonstrates the viability of a novel approach based on stationary time-domain testing and particle swarm optimization. To ascertain the five phase induction machine's electrical specifications, this suggested approach is tested. The goal of this research is to anticipate tunnel boring machine performance by improving the hyperparameters of the support vector machine approach using three different optimization algorithms: moth flame optimization, whale optimization algorithm, and gray wolf optimization algorithm [113].

An extensive and experimental study of the efficiency and harmonic content of three-phase, five-level Cascaded H-Bridges Multilevel Inverters, taking into account various PWM modulation techniques, is presented in this research [114]. The PSO algorithm considers four distinct voltage waveforms and two types of metalized polypropylene power capacitors to determine the parameters of each model by comparing the calculated current flowing through its terminals with a reference current obtained in laboratory tests [115]. For a solar power conditioning system, this research [116] suggests a second-order harmonic reduction method with a proportional-resonant controller. Inverters produce a second-order harmonic at twice the fundamental frequency in a single-phase grid-connected system. Using the Half Height approach, the Modified Particle Swarm Optimization method determines the necessary optimal switching angles to eliminate the desired value of harmonics, which is the main goal for the Voltage Lift Multilevel Inverter [117]. The extensive literature overview on the use of artificial intelligence, digital signal processing, and optimization strategies in PQ disturbance categorization is presented in this work [118]. Levy Flight motivated Adaptive Particle Swarm Optimization is a recently developed swarm-based metaheuristic that is used to solve such complicated, nonlinear, and nonconvex engineering optimization problems [119]. Reconfiguring the distribution network is used here to enhance the power quality and reduce power losses in dispersed networks [120].

This article [121] describes a method for locating and estimating the parameters of the harmonic source with the largest contribution that is based on the particle swarm optimization algorithm with adaptive and individual inertia. In order to determine the best optimization framework to identify switching moments in 11-level multi-level inverters, a number of recent metaheuristics are used in this study, including atom search optimization, artificial electric field algorithm, moth flame optimizer, sine cosine algorithm, flow direction algorithm, equilibrium optimizer, hummingbird algorithm, dragonfly algorithm, harris hawk optimization, and arithmetic optimization algorithm [122]. This research [123] proposes a novel heuristic salp swarm optimization method that dynamically adjusts the PI control settings to appropriately adapt to nonlinear characteristics of induction motors. In the current work, anti-windup PI controller gains are tuned via offline simulation using the particle swarm optimization approach for DC bus voltage management of the shunt active power filter [124]. The periodic harmonic components are simultaneously obtained in [125] by use of the variation mode decomposition technique. The correctness and practicality of the suggested method are confirmed by measured data and simulation analysis. It has been demonstrated that the suggested approach has more application for harmonic detection in power systems when compared to the detection outcomes achieved with the Empirical Mode Decomposition methodology. The hybrid Phasor Particle Swarm Optimization and Gravitational Search Algorithm, a novel hybrid population-based meta-heuristic algorithm, is proposed in this paper to solve the optimal placement and sizing problem of shunt capacitors and inverter-based distributed generation units in radial distribution systems with linear and non-linear loads [126]. In order to accomplish the predetermined active and reactive power sharing ratio between the utility grid and distributed generator (DG) during load switching and DG circumstances, a grid-tied microgrid controller is presented in [127].

In order to verify the superiority of the suggested controller, it is necessary to compare its performance under the same operating circumstances and system configuration with that of its predecessor controller based on the grasshopper optimization method.

A grid-connected microgrid system including solar photovoltaic, wind, micro gas turbine, fuel cell, and battery energy storage is regarded as a test model [128]. The created system is shown as a multi-objective function with limitations that a substantial optimization technique can overcome. The paper's innovation is in its combination of the well-known artificial intelligence approaches with the metaheuristic optimization methodology, which improves the tracking system for maximizing the power harvested from photovoltaic arrays [129]. This work [130] proposes a novel meta-heuristic firefly algorithm optimization technique for passive harmonic filter design that minimizes the harmonics present in the power system environment. This research [131] discusses evolutionary algorithms and metaheuristics that have been suggested for use in a variety of power conversion applications, including DC-DC converters, PWM converters, multilevel inverters, power filters, and FACTs controllers and devices. The Firefly algorithm-based least square approach, a novel hybridized algorithm for power system harmonic estimation, is presented in this research. It estimates the phases using the Firefly algorithm and the amplitudes of the harmonic signals using the least-squares technique [132].

An overview of certain well-known heuristics methods inspired by nature that are also used to harmonics estimation difficulties is given. With their roots in biological, physical, and social processes, these heuristic strategies provide novel ways to solve problems. The investigation includes their fundamental ideas, uses, and flexibility in Harmonics estimation fields.

a) Particle swarm optimization;

A heuristic technique i.e. Particle Swarm Optimization (PSO) is inspired by the social dynamics of bird flocks and fish schools [115]. It has shown to be an excellent solution for signal processing's harmonics estimation problem. In PSO, a swarm of particles moves around the solution space, adjusting their positions according to their individual experiences as well as the collective knowledge of the swarm.

Each particle's location, denoted by a vector j_i , is associated with a possible harmonics estimate solution. Its velocity determines the particle's travel in the solution space v_i. Combining individual and swarm-level information, the particles are drawn to both their global best-known solution, g, and their personal best-known solution h_i.

The location and velocity update equations in PSO are provided mathematically by:

$$\begin{aligned} v_i^{(x+1)} &= a.v_i^{(x)} + p_1.q_1.(h_i - j_i^{(x)}) + p_2.q_2.(k_i - j_i^{(x)}) , \\ j_i^{(x+1)} &= j_i^{(x)} + v_i^{(x+1)}. \end{aligned} \tag{9}$$

In (9), a is weight inertia whil p_1 , p_2 are acceleration constants and p_1 , p_2 denote random numbers. The position of particles is refined until the convergence is achieved.

This PSO based method for estimating harmonics shows how flexible algorithms inspired by nature can be when solving challenging signal processing issues.

b) Ant Colony Optimization;

Ant Colony Optimization (ACO) technique is a heuristic inspired by nature that finds optimal solutions by mimicking the foraging activity of ants [105]. It has been effectively used in signal processing for the estimate of harmonics. Potential solutions are modeled as routes in ACO, and artificial ants walk these roads and leave pheromone trails behind. Subsequent ants follow the pheromone concentration, where higher concentrations denote superior solutions.

Let's depict a solution as a vector X, with Ti denoting the pheromone intensity on the ith component. At iteration i, the probability P that ant K selects component j of the solution is provided by;

$$A_{lm}^{k} = \frac{\mathsf{A}_l^{\alpha} . \partial_{lm}^{\beta}}{\sum\limits_{l=allcom} \mathsf{A}_l^{\alpha} . \partial_{lm}^{\beta}} , \tag{10}$$

where α and β represents control parameters and ∂_{lm} is the desirability of solution.

Updating rule is given as;

$$\mathsf{A}_l = (1 - \mathsf{S}).\mathsf{A}_l + \sum_{l=1}^{m} \nabla \mathsf{A}_l^{k} \quad , \tag{11}$$

S is the evaporation rate, m is no of aunts and $\nabla \mathsf{A}_l^k$ is the total amount of pheromone deposited by k_{th} aunt.

Through several repetitions of iterative refinement, ACO enables the artificial ants to explore the solution space in an adaptable manner. The goal of this procedure is to converge on the best harmonics estimation solution. Because ACO is adaptable, it is a potential method for handling challenging signal processing jobs.

c) Simulated Annealing;

Motivated by the metallurgical annealing procedure, Simulated Annealing (SA) is a probabilistic optimization approach [7]. It has been modified for use in signal processing to estimate harmonics. Through accepting both uphill and downhill motions with a decreasing frequency over time, SA is able to explore globally optimum solutions and break free from local minima.

Suppose j repenting solution, $O(j)$ objective function and T denotes temperature in between the annealing process. The probability denoted by $B(j_i \rightarrow j_k)$ from the solution j_i to j_k is given by;

$$B(j_i \rightarrow j_k) = \exp(\frac{O(j_i) - O(j_k)}{T}) . \tag{12}$$

As the process advances, Simulated Annealing explores the search space with a decreasing likelihood of accepting inferior answers, hence iteratively refining results. Because of this adaptive exploration, SA can effectively handle the intricate optimization problems that come with estimating harmonics.

d) Artificial bee colony;

An optimization method called Artificial Bee Colony (ABC) mimics the foraging habits of honeybees by drawing inspiration from nature [111]. It has been used successfully in signal processing problems including harmonics estimation. Potential solutions are shown in ABC as food sources, and artificial bees visit these sources repeatedly in order to explore the solution space. The method uses scout bees, observers, and employed bees to adaptively seek for the best answer.

Consider a solution y with fitness $f(y)$. Bees employed improve quality of the fitness by modification position using the relation;

$$s_i^e = y_i + \theta(y_i - y_j) , \tag{13}$$

Here θ is random position between -1 and 1 and i, j are random solutions.

By selecting the food source by bees based on probability of quality is defined as;

$$P_i = \frac{f_i}{\sum_{i=1}^{k} f_k}, \tag{14}$$

Where k is the number of bees on duty.

It is the scout bee's responsibility to find new food sources. A food source's fitness will not change after a predetermined amount of iterations, at which point the related bee turns scout and the solution is randomly reinitialized.

The updating is carried out using following relation;

$$y_i^e = \begin{cases} s_i^e, \; if \; f(s_i^e) < f(y_i) \\ y_i, \; otherwise \end{cases} \tag{15}$$

The efficiency of ABC in handling the complexity of harmonics estimation issues can be attributed to its innate ability to explore and exploit in an adaptive manner.

e) Firefly Optimization;

Yang et.al in 2008, developed a formulation that drew inspiration from the flaring characteristic of fireflies [8]. The technique was explained in detail using three rules:

1. Since fireflies are unisex, there is no chance that they will be attracted to one another based on sex.
2. Given that, a firefly's brilliance is its defining feature. The more brilliant firefly will thus gravitate toward the less brilliant firefly. Brightness and attractiveness have an inverse connection with distance; that is, as distance increases, brightness will decrease and vice versa. Relationship preserved the unpredictability of the firefly motions in this way.
3. In order to develop the problem-specific objective function, brightness is a crucial component.

Two key components of the fascination are the variation in light intensity and the firefly' attraction. Firefly appeal is determined by brightness quality, meaning that attractiveness is measured in terms of brightness. The fire fly's brightness B, which is directly related to the objective function f's maximization at a given point x, may be mathematically represented as follows:

$$A(x) \propto B(x) \tag{16}$$

In this case, the observer's eyes or distance determine how appealing A is. d_{ij} among the firefly i^{th} and j^{th}. Brightness B is dependent on distance d in mathematics; so, its exponential function representation is as follows:

$$B = B_p e^{-\sigma d} \; . \tag{17}$$

The initial brightness Bp and the light absorption coefficient σ are represented in the formula above. Regarding the exponential function, attractiveness representative with A is as follows:

$$A = A_p e^{-\sigma d^2} \; . \tag{18}$$

The motion of ith firefly is attracted by jth and is set on by

$$y_i = y_i + Ape^{-\sigma r^2_{ij}} (y_j - y_i) + \beta \varepsilon_i \; , \tag{19}$$

In this expression, ε_i is the vector of randomization and can be pinched by Gaussian distribution and in most cases we take $A^p = 1$, $\beta \in [0, 1]$.

FFO flow diagram is shown in Figure 4.

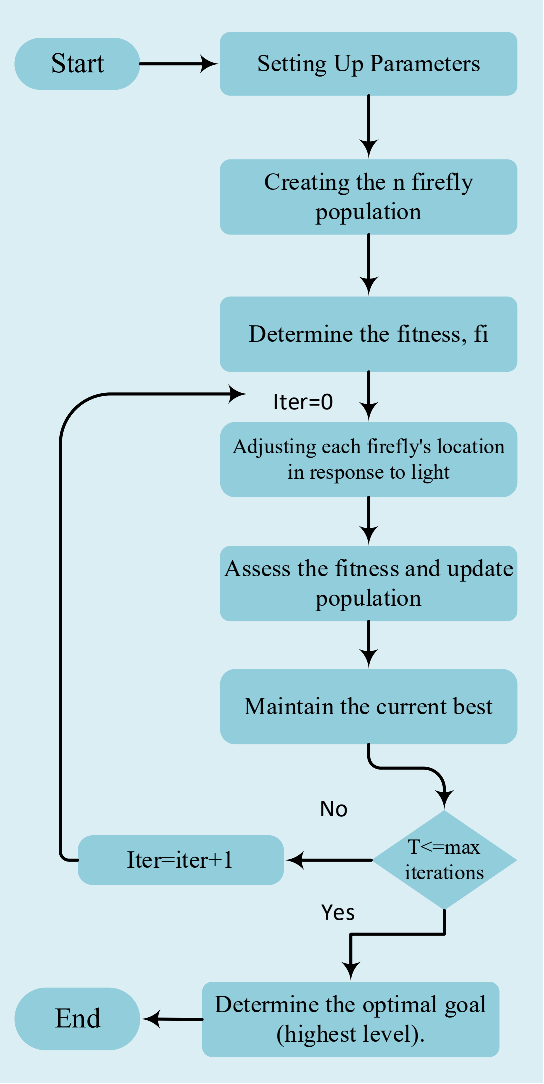

Fig. 4 Flow structure of FFO algorithm.

2. HARMONICS ESTIMATION MODEL

The electrical harmonic signal [8] may be expressed mathematically as follows with regard to the signal's phase, frequency, and amplitude characteristics:

$$y(h) = \sum_{n=1}^{N} a_n \sin\left(b_n h + c_n\right) + \varepsilon\left(h\right), \tag{20}$$

here N is the harmonic order, b_n denotes nth harmonic angular frequency which is defined by $b_n = n2\pi f_0$ and C fundamental frequency, a_n, c_n known as amplitude and phase to n^{th} harmonic, also ε represent white Gaussian noise. Rewriting Eq. (20) as discrete shape through signal sampling $y(h_m)$ with time l, then $h_m = ml$

$$y\left(h_m\right) = \sum_{n=1}^{N} a_n \sin\left(b_n h_m + c_k\right) + \varepsilon\left(h_m\right), \tag{21}$$

Assume $y(h_m) = y(m)$ and modifying (21) as

$$y(m)=\sum_{n=1}^{N}a_n\sin\left(b_n m+c_n\right)+\varepsilon\left(m\right). \tag{22}$$

Using trigonometry to (22)

$$y(m)=\sum_{n=1}^{N}\left[a_n\sin\left(b_n m\right)\cos c_n+a_n\cos\left(b_n m\right)\sin c_n\right]+\varepsilon\left(m\right), \tag{23}$$

Supposing $i_n=a_n\cos c_n$ and $j_n=a_n\sin c_n$. Then, rewriting (23) in basic form as

$$y(m)=\sum_{n=1}^{N}\left[i_n\sin\left(b_n m\right)+j_n\cos\left(b_n m\right)\right]+\varepsilon\left(m\right), \tag{24}$$

Eq. (24) as of the identification model

$$y\left(m\right)=A^t\left(m\right)B+\varepsilon\left(m\right), \tag{25}$$

here

$$A\left(m\right)=\left[\sin\left(b_1 m\right),\cos\left(b_1 m\right),\sin\left(b_2 m\right),\cos\left(b_2 m\right),\ldots,\sin\left(b_n m\right),\cos\left(b_n m\right)\right], \tag{26}$$

Also

$$B=\left[i_1,j_1,i_2,j_2,\ldots,i_n,j_n\right], \tag{27}$$

For minimizing the difference between real $y(m)$ and estimated signal $\hat{y}\left(m\right)$ thus, describing the objective model as;

$$\varepsilon\left(m\right)=\text{mean}\left[y\left(m\right)-\hat{y}\left(m\right)\right]^2=\left[y\left(m\right)-A^t\left(m\right)B\right]^2. \tag{28}$$

The phrases linking the intermediate variables of Eq. (27) has to be applied using the harmonics signal's real characteristics in Eq. (22) since the identification model given in Eq. (25) and the provided cost function in Eq. (28) consider the intermediary variable as parameters to be determined. The desired relation is given as;

$$a_n=\sqrt{\left(i_n\right)^2+\left(j_n\right)^2},\qquad c_n=\tan^{-1}\frac{j_n}{i_n}. \tag{29}$$

Determining the unknown parameters in an engineering mathematical or statistical model to best match observable data is known as parameter estimation and it is an essential component of many scientific fields. In many disciplines, including physics, engineering, biology, economics, and many more, the process is essential. Through the utilization of Web of Science data, scholars may have access to an extensive collection of academic articles, publications, and research findings pertaining to parameter estimation.

A thorough platform for investigating the most recent advancements, techniques, and applications in parameter estimation across a variety of scientific fields is the Web of Science. Through the extraction of useful insights, approaches, and statistical technique developments, researchers may improve and optimize parameter estimate accuracy. The integration of Web of Science data enables a more profound comprehension of the dynamic field of parameter estimate techniques, promoting cooperation and information sharing among scientists worldwide.

According to the Web of Science, 212,842 publications on parameter estimation are written in different fields, which are reflected in Figure 5.

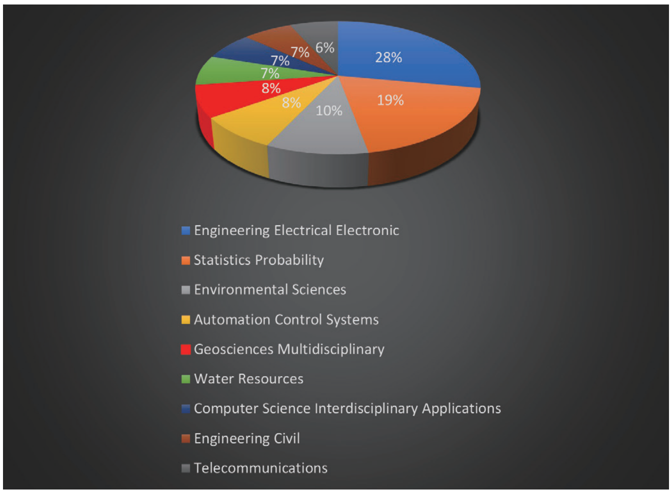

Fig. 5 Statistics of Parameter Estimation in Top Ten Science categories.

Note: Presented information assessed from Web of Science site dated 10-12-2023.

The importance of parameter estimation in driving innovation and technological advancement in the field of Electrical and Electronics Engineering is demonstrated by the 28 percent data representation of parameter estimation in the Web of Science. Applications for Electrical and Electronics Engineering are many and include electrical circuit design, communication networks, signal processing, and control systems.

The field's significant use of parameter estimation suggests that there is a strong emphasis on fine-tuning and optimizing models to faithfully capture real-world occurrences. In order to estimate parameters that are crucial for the design, analysis, and optimization of various systems and devices, researchers and practitioners in the field of Electrical and Electronics Engineering are probably using sophisticated statistical approaches and procedures.

The trend of scholarly publications clearly illustrates the importance of parameter estimation, with a significant uptick in 2021. Of the previous 24 years, 2021 stands out as the peak in terms of the quantity of parameter estimate articles. This increase points to a greater emphasis being placed during that period on developing and improving methods for parameter estimation in a variety of scientific fields.

The bar chart in Figure 6 provides a dynamic narrative of how parameter estimation research trends, methods, and applications have changed over the last twenty years. The 2021 rise may be a sign of new discoveries, developing technology, or a renewed focus on improving models and analysis in a variety of sectors. Scholars and researchers most likely worked on solving current problems, expanding the body of information, and advancing our awareness of the critical function that parameter estimation plays in scientific investigation.

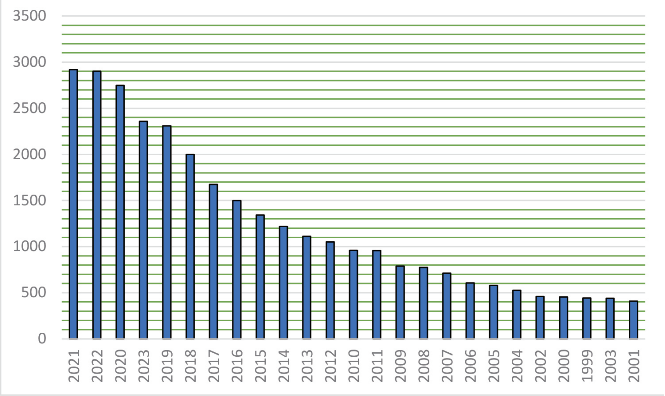

Fig. 6 Statistics of Parameter Estimation for the past two decades.

Note: Presented information assessed from Web of Science site dated 10-12-2023.

A breakdown of parameter estimate publications by nations and regions is shown in Table 1 for top 15 regions. This information shows how researchers throughout the world are participating and contributing to the advancement of parameter estimation. The table provides information on the regional distribution of research activity in addition to highlighting the total amount of publications.

It is essential to comprehend the regional distribution of publications in order to pinpoint regions of interest, prospective joint ventures, and new directions in parameter estimation research. It also offers a foundation for evaluating the worldwide influence of research contributions from various regions of the world. The information provided demonstrates how scientific research is both collaborative and linked, with experts from many places actively contributing to the body of knowledge regarding parameter estimation.

Table 1 Region wise parameter estimation publication data of top 15 regions.

Countries/ Regions	Record Count	Top Author	Number of Publications	Affiliations (Articles)
China	10911	Ding F	219	Chinese academy of sciences (812).
USA	6650	Li J	84	University of California System (666).
France	1954	Tourneret JY	36	Centre national de la recherche scientifique cnrs (905).
Canada	1792	Huang B	34	University of Alberta (198).
England	1644	Wang ZD	92	University of London (172).
Italy	1588	Gini F	35	Consiglio Nazionale Delle Ricerche CNR (154).
India	1572	Dash PK	30	Indian institute of technology system IIT system (588).
South Korea	1330	Kim J	59	Korea advanced institute of science technology KAIST (143).
Germany	1216	Zoubir AM	25	Helmholtz Association (183).
Japan	1197	Yahagi	18	University of tokyo (86).
Australia	1135	Zheng WX	46	University of Melbourne (110).
Spain	979	Camps-Valls G	23	Universitat politecnica de catalunya (152).
Iran	877	Karrari M	25	Amirkabir university of technology (126).
Sweden	780	Stoica P	110	Royal institute of technology (209).
Taiwan	686	Jin S	21	National tsing hua university (88).

Note: Presented information assessed from Web of Science site dated 10-12-2023.

By providing effective answers to difficult issues using clever algorithms and methodologies, computational heuristics significantly contribute to the advancement of electrical and electronics engineering. The Web of Science data indicates that computational heuristics are widely used in this sector, which highlights their significance and influence on research and development.

In computational methods, heuristics are ways of addressing problems that prioritize practicality and speed over assured optimality. Computational heuristics are crucial techniques for solving real-world problems in electrical and electronics engineering, where issues frequently require complex designs, optimization difficulties, and data processing.

In optimization issues like circuit design, signal processing, and control systems, computational heuristics have been a significant contribution. Large solution spaces may be effectively explored by these methods, which aids engineers in quickly locating almost ideal answers. Heuristics like particle swarm optimization, simulated annealing, and genetic algorithms are commonly used in electrical and electronic system optimization.

Furthermore, machine learning and artificial intelligence fields that are now essential to applications in electrical and electronics engineering rely heavily on computational heuristics. These algorithms contribute to breakthroughs in robotics, automation, and smart technologies by making it possible to create intelligent systems for pattern recognition, data processing, and decision-making processes. Computational heuristics are used in signal processing for tasks including signal categorization, feature extraction, and noise reduction. Heuristics have special value in image and audio processing applications because they can handle dynamic and complicated information.

According to the Web of Science data, computational heuristics are widely used in electrical and electronics engineering, which highlights their critical significance in the field's advancement. By enabling engineers and researchers to effectively address difficult problems, these clever problem-solving strategies open up new avenues for advancement and creativity across a range of electronics and technology-related fields.

The examination of Web of Science data during the last ten years has demonstrated the strong effect of computational heuristics in the field of electrical and electronics engineering, as seen in the bar chart shown in Figure 7. The graph offers strong proof of the long-lasting influence and broad use of computational heuristics in this field.

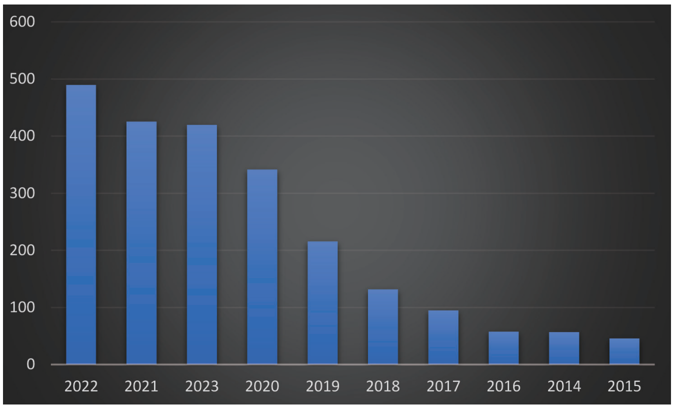

Fig. 7 Statistics of Computational heuristics application for past 10 years.

Note: Presented information assessed from web of science site dated 10-12-2023.

Computational heuristics are used extensively in signal processing to improve algorithm accuracy and efficiency, especially in the area of harmonics estimation. When analyzing any periodic signal, such as an audio signal or an electrical waveform, harmonic components must be identified and analyzed. This process is known as harmonics estimation. Computational heuristics are methods of addressing problems that do not rely just on mathematical procedures, but also on methods based on experience and practicality. Heuristics are frequently used in harmonics estimation to get around problems including fluctuating harmonic content, non-stationary signals, and noise interference.

The 698 papers that were chosen from Web of Science to answer this question demonstrate how interesting and multidisciplinary the field of study that lies at the crossroads of evolutionary intelligence and harmonics is. The extensive literature presumably delves into the connections between complex harmonic patterns which are essential to many natural and artificial systems and evolutionary algorithms, a computer methodology derived from biological evolution. Natural selection and genetic algorithms are the foundations of evolutionary intelligence, which has applications in machine learning, problem-solving, and complex system optimization. The study of frequencies and their interactions, often seen in relation to sound, vibrations, and resonance, introduces an interesting layer to the synergy with harmonics.

Numerous applications, ranging from engineering and optimization issues to the comprehension of intricate biological and ecological systems, maybe the focus of research in this field. Combining harmonics with evolutionary intelligence may result in novel approaches to problems like pattern recognition, signal processing, and creating effective algorithms that can change and adapt to their surroundings. It is probable that the 698 papers address a wide range of subjects, such as theoretical frameworks, algorithmic advancements, empirical research, and real-world applications. Advances in acoustics, signal processing, and evolutionary computing might result from researchers delving into how evolutionary principles can improve the comprehension and control of harmonic events.

The volume of papers that were collected from the Web of Science indicates that there is a thriving and expanding interest in the relationship between harmonics and evolutionary intelligence. This convergence has the power to influence how computational intelligence develops in the future by bringing fresh perspectives, approaches, and uses that cut across many academic fields and increase both theoretical knowledge and real-world applications. 88 academic papers on the topic of harmonics are found by searching the Web of Science database. These articles may provide insightful analysis, new knowledge, and developments in the field of harmonics estimation as shown in Table 2.

Table 2 Statistics of Meta heuristics applied to Harmonics in different fields.

Field	Record count	Top Author (Articles)	Top Regions	Number of publications
Engineering Electrical Electronic	88	Rama G (7)	India	21
Astronomy Astrophysics	71	Althaus LG (5)	USA	24
Computer Science Artificial Intelligence	64	Wang P (4)	India	17
Ecology	38	Farid H (3)	USA	21
Evolutionary Biology	38	Lewis PO (4)	USA	23
Mechanics	38	Kougioumtzoglou IA (6)	China	15
Zoology	38	Feng AS (3)	USA	14
Computer Science Interdisciplinary Applications	32	Hasanvand S (2)	China	12
Computer Science Theory Methods	29	Huelsbergen L (2)	China	7
Optics	29	Gerber G (5)	Germany	8

Note: Presented information assessed from Web of Science site dated 10-12-2023.

3. KEY ISSUES AND CHALLENGES IN HARMONICS ESTIMATION:

Heuristics present a unique set of difficulties even if they are useful tools for estimating harmonics and other complicated issues. The following are some typical difficulties that arise while estimating harmonics using heuristics:

3.1 Balancing Precision and Practicality

Heuristics are frequently best practices that don't always provide extreme precision or accuracy. A high degree of precision is necessary for estimating harmonics, particularly in crucial applications. Only approximations of answers may be provided by heuristics, and the exact heuristic approach used may determine how accurate the results are.

3.2 Challenges of Heuristic Adaptability

There are large variations in the frequency, amplitude, and waveform of harmonic signals. Heuristic techniques that perform well for some signal types might not perform as well for others. It might be difficult to design heuristics that are reliable and work well in a variety of signal situations.

3.3 Computational inefficiency

Numerous heuristic techniques are dependent on the starting conditions and parameter configurations. It might be difficult to find appropriate starting circumstances that produce accurate harmonic estimates in a variety of settings. Certain heuristic techniques could be less appropriate for large-scale systems or real-time applications due to their high computing cost. Algorithm efficiency is critical, particularly in power systems where real-time control and monitoring are necessary.

3.4 Dynamic Challenges in Heuristic Harmonics Analysis

Since power systems are dynamic, harmonic signal properties can alter over time. In situations where signal parameters change, heuristic approaches may not be able to adjust to these dynamic contexts, which might result in decreased performance.

3.5 Complexity in Heuristic Approaches

The performance of heuristic approaches and their complexity are frequently correlated. Better accuracy might be obtained with more intricate heuristics, but at the expense of more computing work. Finding the ideal balance is difficult.

3.6 Adaptability Challenges in Heuristic Techniques

The configurations of power systems can differ greatly, and heuristic techniques designed for one kind of system might not work well for another. It is difficult to make sure that heuristics hold true for a variety of power system setups;

Generally, heuristics don't have theoretical performance guarantees. Heuristics may lack well-defined limits on their accuracy or convergence, in contrast to some optimization techniques that offer guarantees of convergence.

3.7 Comparison Complexity

It might be difficult to assess heuristic methods' performance and compare them to alternative approaches. Meaningful comparisons need the establishment of uniform standards and validation procedures for harmonics estimating methods.

Outlining the benefits and drawbacks of several approaches based on the knowledge acquired is reflected in Table 3.

Table 3 Benefits and drawbacks of various techniques used for power system harmonic estimation [133].

Approach	Reference	Benefits	Drawbacks	Feasible applications
FFT	[134—138]	Easy and Quick.	Picket fence and leakage effects, aliasing, and lost temporal information make it impossible to identify transients.	Linear, stationary signal with a fixed fundamental frequency.
WI-FFT	[139-143]	Less spectral leakage and simple data synchronization.	The estimation accuracy is affected by low-frequency resolution and extra computing load; for example, a DC component may emerge.	Signal that changes over time, featuring interharmonics and frequency deviation.
DWT/WPT	[144-157]	Temporal frequency domain, capacity for many resolutions, and simplicity in filter bank implementation.	Frequency bands make up the spectrum, and the precision is affected by the arbitrary mother wavelet spectrum.	Location of disturbances and data compression.
HHT	[158-162]	The primary purpose of posteriori data processing is adaptability.	To understand conveyed parameters, further tools are required.	Nonlinear and non-stationary signal, offline analysis.
CZT	[163-168]	Flexibility in terms of sample size and data collecting.	More computationally intensive and requiring greater data storage.	Synchronization and time interpolation of data between sample rates.
AR/ARMA	[169-171]	Good accuracy with short data length, no side lobes, and high resolution.	Model order selection is important and affects accuracy since it is unable to resolve near frequencies.	Analysis of the interharmonized signal, transient peak.
PRONY	[172-180]	Able to identify every signal's characteristic, including phase, frequency, amplitude, and damping factor Superior resolution and absence of side lobes.	Computationally inefficient, extremely vulnerable to noise, and mismatched models.	Ideal for data that behaves linearly, accurate offline analysis.

MUSIC	[181-182]	A small data length and good accuracy.	Prior understanding of the frequency search range is required. lengthy computation.	High accuracy frequency identification in an offline application.
ESPRIT	[183-188]	High resolution, accurate estimations of frequency.	Frequency domain only; heavy computational load.	Fixed information, Categorization.
KF	[189-204]	Dependable in the face of loudness, Inverse, The capacity to monitor time-varying parameters.	State variable modeling is essential. filter sagging away, Prior knowledge of the noise and method is required.	Time-varying signal with noise and enough process information for online control applications.
ANN(BPN)	[205-219]	Self-adjusting, Generally accurate even when dealing with noisy data samples.	Greedy nature, multilayered complicated structure,maybe imprisoned in the nearby minima.	A small number of distinct harmonics are essential.
ANN(RB-FNN)	[220-221]	Streamlined architecture, rapid convergence.	Inaccurate when noise and transients are present.	Only a small number of distinct time-varying signal harmonics are more significant.
ADALINE	[222-224]	Strong against interference, improved convergence.	If there are any harmonics in the signal that are not present in ADALINE, it is inaccurate.	Time-varying online tracking harmonics.
EPLL	[225-230]	Able to adjust to changing frequency.	Reduced dynamic response speed.	Fluctuating nonstationary signal frequency.

4. PROPOSED FUTURE PROSPECTIVE

By creating benchmark datasets for rigorous assessment, hybrid approaches that integrate heuristics with other methodologies, and increasingly complex heuristic methods, researchers and practitioners in the area are constantly tackling these problems. These difficulties could be lessened as science and technology advance, but they should still be taken into account when using heuristics to estimate harmonics. Future directions and suggestions for heuristic-based harmonics estimation entail resolving present issues and utilizing cutting-edge technology. The following are some possible paths that heuristics in the area of harmonics estimate might go in the future:

- To construct hybrid models, combine heuristics with additional cutting-edge strategies like machine learning algorithms or optimization approaches. This may improve harmonics estimation's precision and effectiveness by combining the advantages of many strategies.
- Create heuristics that are flexible enough to adjust to shifting power system circumstances and signal properties. This includes the capacity to dynamically modify tactics and settings in response to the harmonic signals' ever-changing nature.
- Prioritize the creation of heuristics that can be used in real-time. This is especially significant for power systems since preserving power quality depends on the prompt identification and suppression of harmonics.
- Examine heuristics that may be applied to various power system sites. Distributed harmonics estimates can offer a more thorough picture of the harmonic content throughout the whole network, particularly with the rising decentralization of power generation.
- To estimate harmonics, use data from Internet of Things (IoT) devices and smart grid technology. The combination of these technologies has the potential to yield an abundance of data for enhanced real-time monitoring and estimating accuracy.
- Improve the heuristics' resilience to deal with a variety of changing signal situations. Make sure heuristics are highly generalizable to various operational conditions and power system setups.
- Establish standardized benchmarks and evaluation criteria for harmonics estimation heuristics. This will facilitate fair comparisons between different methods and encourage the development of more effective techniques.
- The creation of heuristics that are precise and offer explanations for their conclusions should be emphasized. Reliability and interpretability of the models are crucial for building confidence in the outcomes, particularly in important applications;
- Look into heuristics that have the ability to continually learn and adjust to power system changes over time. Online learning strategies might be useful in settings where harmonic properties can change;
- To provide comprehensive solutions and encourage cooperation amongst researchers in the fields of power systems, optimization, and signal processing. More efficient heuristics that take into account the unique difficulties of power systems, as well as the signal processing components, may result from this multidisciplinary approach;
- Promote the creation of open-source systems that use heuristics to estimate harmonics. In the research community, cooperation can hasten advancement and result in the adoption of standardized instruments and procedures.

Through the implementation of these suggestions, scholars and professionals may further enhance the field of heuristic-based harmonics estimate, resulting in more resilient, flexible, and instantaneous power quality monitoring systems for dynamic power grids.

5. CONCLUSIONS

A thorough discussion of the history, state of the art, and potential future directions of heuristics in the field of power system harmonics estimate is provided. The paper traced the evolution of heuristics throughout history to tackle the challenges of harmonic analysis, illuminating their iterative, crude techniques that have been useful in real-world scenarios.

The analysis of the present situation demonstrated a wide variety of heuristics used for the estimate of harmonics, including methods based on the Fourier transform, wavelet transform, and hybrid approaches that use machine learning. This investigation demonstrated how heuristics may be adjusted to different signal situations and how they can be used in real-time in the dynamic world of contemporary power systems. But the trip through the present situation also revealed a number of difficulties. Three key challenges remain: computing economy, accuracy, and adaptation to non-stationary settings. The current difficulties in the use of heuristics for harmonics estimation are further highlighted by their sensitivity to initialization, the trade-off between complexity and performance, and the requirement for standardization in benchmarking.

The use of heuristics in harmonics estimate seems to have bright futures. Strategies for resolving present issues include suggestions for adaptive models, hybrid strategies, and real-time implementations. Incorporating heuristics with cutting-edge technology like the Internet of Things (IoT) and smart grid innovations has promising prospects to improve harmonics estimate efficiency and accuracy. As the area develops, multidisciplinary cooperation and the creation of open-source platforms can hasten the process and encourage a team effort to overcome obstacles and push the limits of harmonics estimating algorithms. Essentially, this study provides academics and practitioners with a roadmap to navigate the always changing field of heuristics in the quest of precise and effective power system harmonics estimate, in addition to acting as a snapshot of the present state of the art.

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