Swarm Intelligence-Based Optimization Techniques for Dynamic Response and Power Quality Enhancement of AC Microgrids: A Comprehensive Review

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ABSTRACT The increasing penetration of Microgrids (MGs) into existing power systems and ''plug and play'' capability of Distributed Generators (DGs) causes large overshoots and settling times along with various power quality issues such as voltage and frequency flickers, current harmonics and short current transients. In this context, over the past few years, considerable research has been undertaken to investigate and address the mentioned issues using different control schemes in conjunction with soft computational techniques. The recent trends and advancements in the field of Artificial Intelligence (AI) have led the development of Swarm Intelligence (SI) based optimized controllers for smooth Renewable Energy Sources (RES) penetration and optimal voltage, frequency, and power-sharing regulation. Moreover, the recent studies have proved that the SI-based controllers provide enhanced dynamic response, optimized power quality and improved the dynamic stability of the MG systems as compared to the conventional control methods. Their importance in modern AC MG architectures can be judged from the growing number of publications in the recent past. However, literature, pertaining to SI applications to AC MG, is scattered with no comprehensive review on this significant development. As such, this study provides an overview of 15 different SI optimization techniques as applied to AC MG controls from 43 research publications including a detailed review of one of the elementary and most widely used SI based metaheuristic optimization algorithms called Particle Swarm Optimization (PSO) algorithm. This comprehensive review provides a valuable one-stop source of knowledge for the researchers and experts working on SI controller's applications for AC MG dynamic response and power quality improvements.

INDEX TERMS AC micro-grids, optimization, artificial Intelligence, swarm intelligence, power quality, dynamic response enhancement.

ABBREVIATIONS

AI	Artificial Intelligence	CSPI	Critic based Self Tuning of Proportional Integral Controller
ALO	Ant Loin Optimization		
ANFIS	Adaptive Neuro-Fuzzy Inference System	DES	Distributed Energy Sources
ANN	Artificial Neural Network	DFIG	Doubly-Fed Induction Generator
ANN	Artificial Neural Network	DG	Distributed Generator
BB-BC	Big Bang-Big Crunch	DVR	Dynamic Voltage Restorer
BFO	Bacterial Foraging Optimization Algorithm	FF	Fitness function
		FL	Fuzzy Logic
		FL	Fuzzy Logic

FLC	Fuzzy Logic controller
FOA	Firefly Optimization Algorithm
GA	Genetic Algorithm
GDC	Generalized Droop Coefficients
GOA	Grasshopper Optimization Algorithm
GOA	Grasshopper Optimization Algorithm
GRNN	General Regression Neural Network
HBB-BC	Hybrid Big Bang-Big Crunch
HBELA	Human Brain Emotional Learning Algorithm
IAE	Integral Absolute Error
ILC	Iterative Learning Controller
IPSO	Improved Particle Swarm Optimization
ISE	Integral Square Error
ITAE	Integral Time Absolute Error
ITSE	Integral Time Square Error
MG	Microgrid
MGCC	Microgrid central controller
PI	Proportional Integral
PV	Photo-Voltaic
PWM	Pulse Width Modulation
RBFNN	Radial Basis Function Neural Network
RES	Renewable Energy Sources
SHE	Selective Harmonic Elimination
SI	Swarm Intelligence
SOA	Seekers Optimization Algorithm
SOC	State of Charge
SSA	Salp Swarm Optimization Algoirthm
SSA	Slap Swarm Algorithm
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
SVPWM	Space Vector Pulse Width Modulation
UPQC	Unified Power Quality Conditioner
VAR	Volt Ampere Reactive
VF	Voltage Frequency
VFOC	Virtual Flux Oriented Controller
VSI	Voltage Source Inverter
WOA	Whales Optimization Algorithm
Z-N	Ziegler Nichols

SYMBOLS

f	Frequency
J_1	Objective Function 1
J_2	Objective Function 2
K_d	Derivative Gain
K_i	Integral Gain
K_p	Proportional Gain
P	Active Power
V	System Voltage
i_d, i_q, v_d, v_q	Current and voltage in d-q reference frame
$V*$, $f*$	Voltage and frequency reference values
$P*$, $Q*$	Active and reactive power references
$i*$	Current reference value
vf	Voltage-frequency control
PQ	Active and reactive power control

I. INTRODUCTION

Microgrids (MGs) are becoming more and more intelligent, distributed and flexible. Advanced power-electronic devices and Artificial Intelligence (AI) techniques are dominating the electrical grids and this trend may still last for many coming years [1]. The growing implementation of advanced AI techniques in MG controls is significant and ensures smooth integration and disconnection of DGs, enhanced power quality for the end-user and improves the transient stability of the power system. Hence, MGs are emerging as a reliable and cleaner source of energy.

An MG is basically a cluster of loads and micro-sources such as wind turbines, micro-turbines, solar Photovoltaic (PV) and fuel cells operating as a single controllable system that delivers both heat and power to the local area [2]. A typical structure of MG is shown in Figure 1. The interconnection of MG with the utility grid generally require a non-linear power electronic device such as pulse width modulated voltage source inverters (PWM-VSI), or the converters. These power electronic devices play a vital role in integrating Distributed Energy Resources (DER) into the utility grid and regulating the power flow between DGs and the main grid [3]. The major problem associated with these devices is that they produce non-linearity between voltage and current due to the generation of high switching frequency pulses which in-turn distorts the power quality of the system [4]. Hence MG faces severe challenges regarding power quality and security especially when integrating an excessive number of DGs into the power system [5]. A general configuration of AC MG is shown in Figure 1 which comprises of two DGs; each one connected to the point of common coupling (PCC) through a power electronic interface. In order to satisfy the power quality standards and to ensure the smooth operation of the power system during and after the grid connection, a robust control strategy is essentially required. Also, optimal parameters of the selected controller, filters and other connected devices are necessary to obtain an optimal dynamic response, smooth transition, minimum settling time and overshoot.

The serious problems that affect the power quality of MGs can be classified on the basis of the their operation mode. In islanded mode, the MGs' voltage and frequency profiles have to be established by their control itself, otherwise, the system will collapse due to the sensitivity of the connected DG units and lack of support from the main grid [6]. Furthermore, the harmonic distortion of the output power waveforms is a critical problem that is often caused by the high-speed operation of the inverter switches. The long transient period can affect all system equipment regardless of whether it occurs in the islanding of DGs or during an abrupt load change [7], [8]. On the other hand, MG in grid-connected mode also faces issues that can substantially influence the power supply quality. For example, the behavior of the MG is mostly dictated by the bulk power system, therefore, regulating the flows of both active and reactive power is an essential control objective for managing the MG's output power [9]. In addition, the power quality of supply also need to be
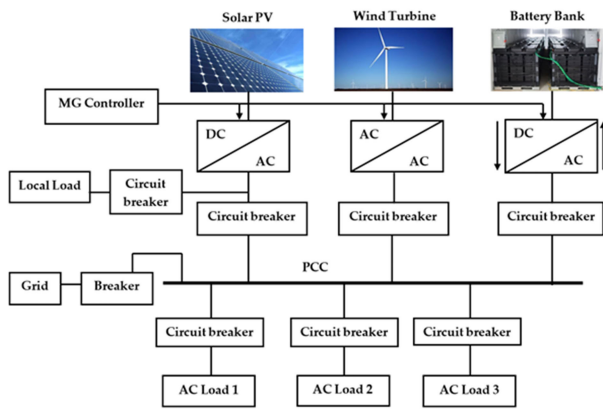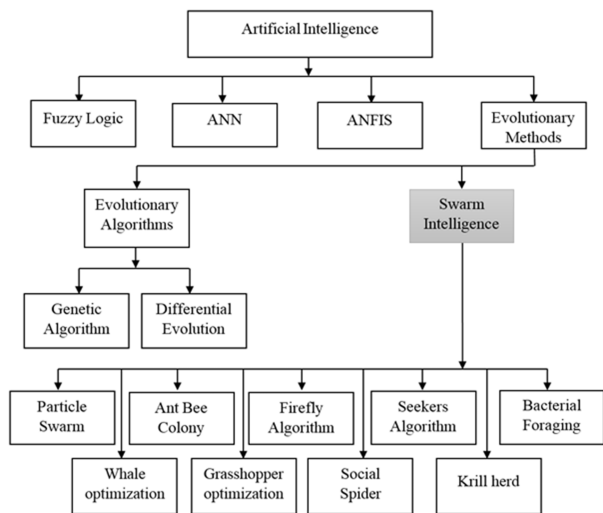
FIGURE 1. A basic structure of AC MG.

FIGURE 2. AI-based optimization technique used to solve power quality issues in the MG system.

monitored and maintained within the specified limits in order to achieve stable power system operation.

Recently, with the advancement in the field of soft computational techniques, these objectives are effectively accomplished by using AI control schemes. AI is a type of humanly created software or machine intelligence which substantially decrease the workload of human [10]. AI can be broadly defined as the automation process based on human wisdom, such as problem-solving, decision making, perception, reasoning, and learning [11]. It is established from the literature that; AI techniques outperform conventional techniques in terms of robustness, stability and response time. However, the conventional techniques, it needs memory to achieve the aforementioned tasks. As such, the inclusion of few additional features in AI controllers makes them more expensive than the conventional techniques [10]. Figure 2 shows several important categories of AI as reported in the literature for solving MG power quality issues.

Since it is quite difficult to justifiably cover all the AI methods as applied to the current study, hence the scope of the study has been restricted to only one of the most modern classes of AI techniques called Swarm Intelligence (SI). Each of the mentioned SI techniques has been extensively explored in literature and found useful in addressing the dynamic response and power quality issues of the AC MGs. However, despite their vast applicability in the mentioned area of research, there is not a single one-stop source that provides a comprehensive summary and review of such studies. Most of these scattered publications on SI based MG controllers can be found in electrical, computing, energy and electronics application-related journals. Unlike SI-based MG control strategies, the conventional control methods of MG controls are well summarized and their reviews have been produced in various studies like [12], [13]. As such, there is dire need to fill this gap in the literature by reviewing and compiling all SI-based MG control articles for the power quality and dynamic response improvement of the MGs in a single reference. It is, therefore, this review study is undertaken with the aim to highlight the growing impact of SI techniques in meeting AC MG power quality standards. While doing so, each SI method as applied to MG controls has been reviewed along with the methodology and outcomes of the considered research work. Finally, this study at conclusion also provides a future outlook pertaining to SI controller applications in the field of AC MG controls.

In order to achieve the stated aims of this study, Section II describes the methodology and scope of the presented review. Section III of this dissertation is dedicated to modern MG control schemes used for dynamic response and power quality enhancement of AC MGs. In section IV, the basics of SI along with its merits and demerits are discussed in detail. Section V of this paper highlights the role of SI based optimization methods in MGs' dynamic response and power quality enhancement. Particle swarm optimization basics and its application in the current subject is discussed in Section VI. Modern SI-based optimization techniques as applied to power quality and dynamic response enhancement of AC MGs is discussed at length in Sections VII. The conclusion and future outlook pertaining to SI controller applications in the field of AC MG controls are provided in Section VIII of the paper.

II. REVIEW METHODOLOGY AND SCOPE

This section provides the information about the methods used for selection of published articles for the review purpose in the current study. Three of the major online services namely, Google Scholar https://scholar.google.com, Web of science http://webofknowledge.com and Scopus https://www.scopus.com have been used for selection of articles on mentioned area of research. For searching the relevant material online, following keywords were used; power quality enhancement of MG, optimized dynamic response enhancement of AC MG, optimized voltage and frequency regulation of islanded AC MG, optimized power flow control in a grid-connected MG and optimization of dynamic

TABLE 1. Classification of articles selected for the current study.

Classification basis		Articles
MG Operating Mode	Islanded	[14]- [37]
	Grid tied	[38]- [50]
	Both	[51 - 56]
SI based Studies	PSO	[14] - [22], [38]- [46], [50]- [56]
	Modern SI technique	[23]- [37], [47]- [49]

(a)

(b)

FIGURE 3. (a) MG along with control scheme (b) working mechanism of *vf* and *PQ* controller.

response and power quality of hybrid renewable energy source using swarm intelligence. A further screening was made, and priority was set based on the quality of the journal, impact factor, Scopus indexing and lastly the conference papers. The content power quality and dynamic response enhancement of AC MG using a swarm intelligence based optimization technique is set as the very basic criteria of selecting a paper for review. Considering the length and space constraints of the article, 43 of the recently published research articles on SI based MGs were selected to explore 15 latest SI based techniques used in the MG control architectures for the dynamic response, stability and power quality enhancement. After studying and analyzing the selected articles carefully, an outline was prepared for the review. Finally, the arrangement of the sections has been carried out in such a way that each section must have some relation and coherence to its preceding section. In addition, the current review has made different classifications of the modern SI based control architectures based on MG operating mode, SI method used, fitness function (FF) formulation, number of optimized variables, objective of the study and DG used. All the mentioned parameters are tabulated in a useful way for the easy understanding of the researchers working in the mentioned area of research. For the ease of the readers, a classification of all the considered articles is made based on the MG's operating mode and applied SI based techniques and is presented in the tabular form in Table 1.

III. MODERN MG CONTROL SCHEMES FOR DYNAMIC RESPONSE AND POWER QUALITY ENHANCEMENT
In this section, the control schemes that have been utilized for the frequency, voltage and power regulation of both island and grid-connected MGs are discussed with a major focus on the current study objectives. An intelligent and robust control scheme ensures the robust and reliable operation of an MG. In addition, an efficient control structure in an inverter-based MG plays a vital role in meeting the power quality standards [57]. A generalized structure for both islanded and grid-tied MGs along with the voltage-frequency and active-reactive power control schemes is shown in Figure 3.

The control objectives in shown MG controller are fairly accomplished using PI regulator based power and current control loops. The current control loop is used to improve the quality of the inverter output current while the power control loop regulates the inverter output power along with providing a refined reference signal to the current controller. Based on
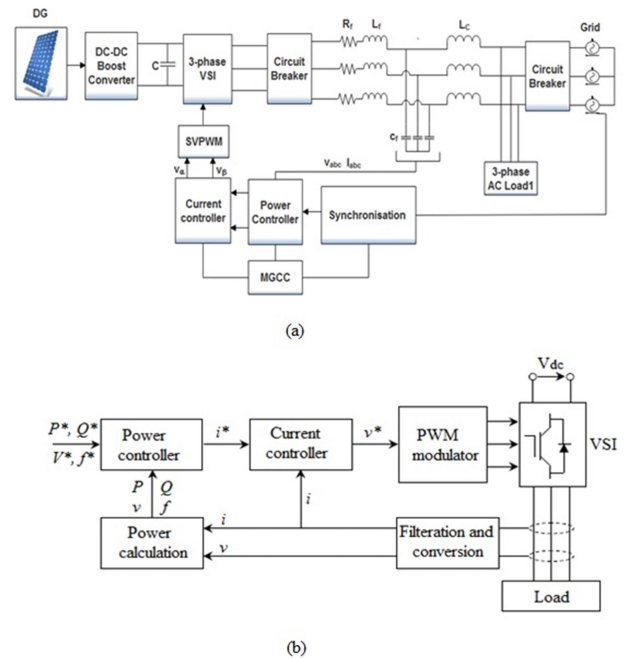
the operation of the MG (islanded or grid-connected) and control objectives, the reference signals are decided by the control designer. In case of the islanded mode, since the control concern is regulation of voltage and frequency at their nominal values, the reference values are generally set as *V** and *f** while in grid-connected mode the reference points are set as *P** and *Q** in order to make the DGs achieve set reference active and reactive power [58]. A detailed discussion of both the control modes of MG is made in the subsequent subsections for a better understanding of two different aspects of the MG control objectives i.e. voltage-frequency control and power flow control.

A. MG VOLTAGE AND FREQUENCY CONTROL
Due to the non-linear nature of DC/AC and AC/AC converters and abrupt load and source changes during the normal operation of an MG, the deviations in the voltage and frequency are inevitable. The basic objective of an MG controller is to minimize such deviations in order to provide a high quality power to the end-user [2]. In grid-connected mode, owing to the stiff operational characteristics of the main grid, the system's voltage and frequency control is generally not needed. However, this type of control can be added as an optional control in cases where the grid is not strong as compared to the MG which is usually not the case. In the case of islanded operation of the MG, the regulation of voltage and frequency is the prime objective of the controller and hence the controller must maintain the nominal voltage and frequency of the system under all operating conditions.

One of the important factors that need to be considered for evaluating the voltage profile of an MG is the harmonic

distortion level, which is the measure of the amount of distortion level present in a sinusoidal voltage waveform. The major reason for this distortion is high-switching operation of the inverter which leads to the overheating of the connected equipment and causes decline of the power factor. Hence, in order to maintain the voltage profile in such inverter-based MGs, the mitigation of harmonics is necessary and is generally done by utilizing the coupling transformers and filters at different stages of the system [59]. Furthermore, abrupt load changes and fluctuated nature of power supply from DGs can also cause severe voltage sags and swells in MGs [60].

To overcome the above-mentioned issues and to maintain the voltage profile of the MG system, several methods are proposed in the literature. One of the solutions is to inject reactive power sources at the point of common coupling. This reactive power source may be an inverter-based DG [61] or active power filter [62] or a synchronous compensator [63]. In references [64] and [65], the authors used droop control for voltage and frequency regulation of the MG. Droop is one of the simplest methods for the voltage and frequency control in both conventional power systems and MGs, however, due to the difficulty in managing the droop characteristics, the voltage and frequency might be settled to some new points which may not be same as their nominal values. The droop coefficients can be optimized by an SI method in order to set the droop characteristics optimally as done in references [54] and [53]. However, it will increase the complexity and time of the simulation due to addition of two more variables (droop coefficients) in optimization process. Therefore, in order to improve the voltage profile of the MGs, most of the researchers working in this area of research have either worked on optimal placement of DGs [66] or optimizing the control parameters that are responsible for optimal transient response and stable operation of the studied MG design [55].

B. MG ACTIVE AND REACTIVE POWER CONTROL

Active and reactive power control (generally referred as *PQ* control), is an important control aspect for an MG controller in both modes of MG's operation especially in grid-connected mode. The effective power-sharing control scheme ensures reliable operation of the MG by effectively managing the imported and exported power between the MG and the main grid as per the requirement. For the islanded mode, the *PQ* control is given secondary importance and it may be improvised in islanded control structure based on the requirement. Contrary to that, in the grid-tied mode each DG unit is operated as a source of active-reactive power and is required to inject a defined amount of power to the power system [6]. Since in grid-connected mode, the behavior of the MG is dictated by the giant power system, the *PQ* control is essentially required in order to regulate the active and reactive power flow and hence effectively managing the output power of the MG [9].

Several methods have been proposed in the literature to achieve effective *PQ* control with suitable power quality. In references [67]–[69], the active and reactive power output of a grid-tied inverter-based DG unit was regulated by adjusting the power angle and the filter capacitor's voltage respectively. The aim of all the mentioned studies was to achieve a fast dynamic response and least static error. Wang *et al.* [70] used a model predictive method that ensures faster dynamic response in power-sharing during both the grid-tied and islanded mode of MG operation. In the mentioned work, the solar PV and battery storage inverters worked in current control mode during the grid-tied mode while they were made to operate in voltage control mode during islanded operation. A similar configuration as that of [70] was used by Wu *et al.* in [71], where the power regulation was carried out in decentralized manner by tracking the bus frequency. It is important to note that the conventional *P-f* and *Q-V* droop control is more suitable for power-sharing among DG sources in highly inductive nature of distribution network whereas a modified or reverse *P-V* and *Q-f* droop power sharing control is applicable for VSI of the DG sources in MG power system with resistive nature of low voltage network [72], [73]. The mentioned droop controllers assigned the amount of power-sharing for load changes automatically without any dedicated communication link. Recently, the power flow control objectives in MGs are fairly accomplished by using conventional PI controller based power and current control loops such as in references [74]–[76]. The controller in mentioned studies achieves the desired power-sharing ratio with suitable dynamic response, however, the developed controllers face a common problem that is the lack of automatic parameter tuning which causes comparatively large overshoot and settling time during the abrupt load changes. Hence an optimization method is required to select the best possible values of the controlling parameters in order to optimize the dynamic response of the system and to enhance the system performance and stability. Since it is very difficult to cover all the optimization methods used in MG application, the scope of the current study is restricted to "swarm intelligence" based optimization techniques only.

IV. SWARM INTELLIGENCE (SI)

A "Swarm" is defined as a large number of interacting and decentralized homogenous agents that work collectively to achieve certain objectives. In this context, the SI can be defined as a branch of AI that is used to model the collective conduct of the natural social swarms, such as fish schooling, ant colonies, bacterial growth, animal herding and bird flocking [77]. The SI based algorithms have emerged as a family of nature-inspired, population-based algorithms that are capable of producing robust, time-saving and cost-effective solutions to numerous complicated optimization problems. Even though the individual agents in a swarm possesses limited intelligence and skills, their interaction with each other and environment produces certain social patterns that allow them to achieve their collective goals such as
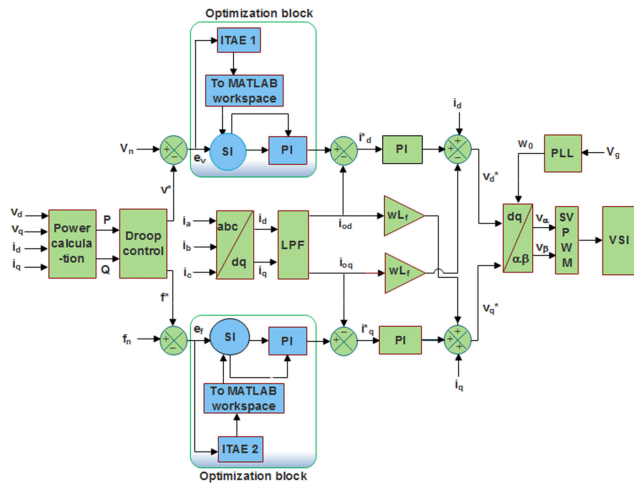
FIGURE 4. Detailed diagram of SI-based islanded MG vf controller [17], [24], [26], [36], [50].
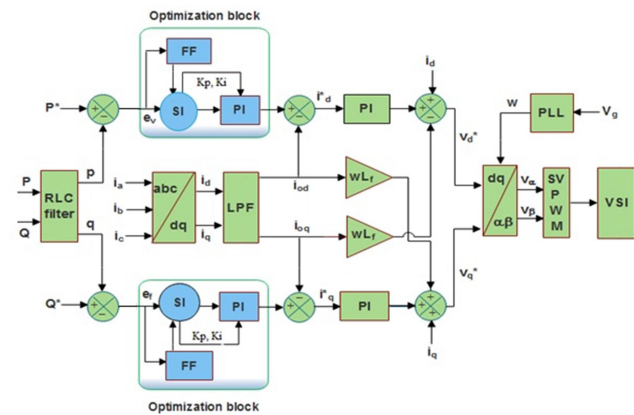

FIGURE 5. Detailed diagram of SI-based grid-connected MG PQ controller [39], [50].

finding a food source or exploring an optimal route to their destination.

The term "Swarm Intelligence" was coined by J. Wang and G. Beni in 1989 to solve the global optimization problems in the field of robotics [78]. Since then, the SI based algorithms have attained significant popularity among the researchers and are considered as one of the most promising categories of AI. This can be realized by the growing number of SI based studies which consequently led the conception of dedicated journals and conferences on this important subject [79]. Few of the detailed SI application-based studies are provided in references [80]–[83]. As such, this research work aims to highlight only one of the important applications of SI based techniques in the field of electrical engineering.

A. ADVANTAGES OF SI BASED SYSTEMS
The major advantage of SI based systems include;

1) COLLECTIVE ROBUSTNESS
Since SI systems operate collectively without any central control and no individual searching agent is decisive for the continuation of the swarm, they are robust in their very basic operating mechanism. Due to the above-mentioned ability of the SI systems, they can sustain the failure of an individual search agent without any significant adverse affect on the swarm population [84].

2) ADAPTABILITY
Due to the inherited self-organization and auto-configuration capabilities of the SI systems, they can automatically adapt to the rapidly changing operating conditions. Hence, such systems can dynamically adjust their behavior on run-time according to the external environment, with substantial flexibility [85].

3) SCALABILITY
SI systems are highly scalable. This is because of the reason that their control mechanism is not dependent on the swarm size extensively [85].

4) INDIVIDUAL SIMPLICITY
Despite very simple nature and limited inherited capabilities of individual agents in an SI based system, their collective behavior is practically sufficient to achieve the collective goals of the swarm [84].

B. DISADVANTAGES SI BASED SYSTEMS
Despite having the aforementioned advantages, the SI algorithms suffer from the following major limitations.

1) PARAMETER TUNING
Unlike the deterministic optimization methods, the parameter tuning of the SI based optimization algorithms is problem-dependent. Hence they are either selected empirically by using trial-and-error or by making them adaptive i.e. a function of the iteration number during run-time [86].

2) TIME-CRITICAL APPLICATIONS
Due to the stochastic nature and unpredictable behavior of the SI based systems, they are not suitable for the applications that require time-based critical decisions or online control [85].

3) STAGNATION
Due to the lack of central coordination, the SI systems may prematurely converge and stick to a local optimum. However, this problem can be solved by setting the algorithm parameters carefully.

It is worthwhile to mention that the SI-based algorithms do not completely establish their superiority over other optimization techniques on static problems whose conditions and characteristics do not vary over time [87]. Nevertheless, due to their inherited adaptive capabilities, they are often

more competitive to deterministic approaches in dealing with uncertainty, as well as general-purpose heuristics approaches (e.g., simulated annealing and hill-climbing) in dealing with stochastic time-varying problems [88].

V. ROLE OF SI BASED OPTIMIZATION TECHNIQUES IN AC MG CONTROLS FOR DYNAMIC RESPONSE AND POWER QUALITY ENHANCEMENT

The major power quality and dynamic response problems in the MGs occur due to the ''plug-and-play'' capability of a huge number of DGs and loads. The transition from grid-connected to the islanded mode and vice versa also causes a considerable mismatch between the generated power and connected load and hence the severe voltage and frequency deviations are inevitable [89]. In order to cope up with these problems, an efficient control strategy is essentially required whose job is to ensure stable operation of the power system with minimized overshoot and settling time during the mentioned conditions.

For the grid-tied mode, there is no requirement of the voltage controller as the voltage is dictated by the main grid while the power controller may be replaced by a voltage controller in case of the autonomous mode. A detailed diagram for a typical MG, such as shown in Figure 3, operating in autonomous and grid-connected mode with SI based parameter tuning is pictured in Figure 4 and Figure 5 respectively.

Figure 4 and 5 shows a general structure of the SI based voltage-frequency (*vf*) and power flow regulation controller respectively. Several authors utilized these control structures along with different SI techniques to optimize the system response. Al-Saedi *et al.* [17], [39] and Chung *et al.* [54] used PSO, Qazi *et al.* used WOA [36] while Jumani *et al.* [24], [50] used GOA to optimize the system response using mentioned control architectures. It may be noted from the above research works that the most widely used controller in the power, voltage, and current control loops is conventional PI controller due to its easy realization, simple implementation and suitable reliability [90], [91]. However, the major limitation of using such a controller is that its performance is purely dependent on the suitable tuning of its gain coefficients (K_p and K_i) [92]. The optimal tuning of these gain values ensure enhanced power quality and improved system performance during disturbance and load changes [55]. A considerable research work has been carried out to find the optimal values of these PI gains according to the operating conditions of the MG. Katiraei and Iravani [64] and Sao and Lehn [93] used the ''trial and error'' method to get the suitable values of PI gains. This method of parameter selection is easy and simple but does not guarantee the optimal selection and is also time-consuming. Furthermore, the parameters selected are only valid for the selected operating conditions. In some other studies [94]–[96] the the authors used Ziegler-Nichols (Z-N) method to tune the PI controller in an MG control architecture. The limitations related to Z-N technique are that it is time taking tuning process and generally cause a delay while entering an unstable region of operation [97]. Owing to

the above-mentioned issues, recently SI techniques are used effectively to optimally tune the parameters of PI controllers in order to achieve the improved power quality and enhanced MG performance. In addition to the PI gains, the researchers have also optimized the value of droop coefficients [54], LC filter values [55] and the dc link capacitance value [37] in order to search for wider range of possible combination of system optimal parameters. It is worthwhile to mention that, increasing number of optimization variables increases the possible number of solutions and solution quality, however, it would increase the time consumption for the optimization process. Hence greater number of iterations are required to reach the optimal value of the FF.

Optimization is defined as the process of searching for the best possible values of variables by minimizing or maximizing the given objective function under certain defined constraints [98]. In order to solve the optimization problem, different steps are required to be accomplished. The foremost step is the identification of the parameters that need to be optimized. Secondly, based on the nature of the parameters, a FF or objective function (OF) is formed which needs to be minimized or maximized in order to get the optimized set of parameters. Thirdly, the constraints need to be set, if any. Finally, based on the identified parameters, constraints and number of objective functions, an appropriate optimizer is employed to solve the optimization problem. It is important to note that a good SI optimization algorithm should possess the potential of pushing the search agents towards the global optimum continuously in order to find a better solution by exploring and exploiting the defined search space. Some of the very important features of a good optimization algorithm are listed as follows [99].

1) The algorithm should keep the best-obtained solution after each iteration and assigns it to the global optimum variable.
2) It must have the capability to record the history so that the best solution obtained so far may not be wiped out even if the whole population deteriorates.
3) The algorithm should efficiently explore the search space at starting and exploits it at the end so that an optimal solution may be obtained effectively.
4) The algorithm should possess the capability of avoiding stagnation into local optima.
5) Parameters of the algorithm must possess adaptiveness so that the algorithm can explore and exploit the search space at the beginning and ending phase respectively.
6) The algorithm should not be complex in its working mechanism.

The above-mentioned merits of an algorithm make it potentially able to solve the optimization problems in an efficient way. In order to have a better understanding of how an optimization algorithm works, a generalized flow chart of the SI optimization methods is shown in Figure 6.

In most of the SI optimization techniques, the parameters of the selected optimization algorithm are defined
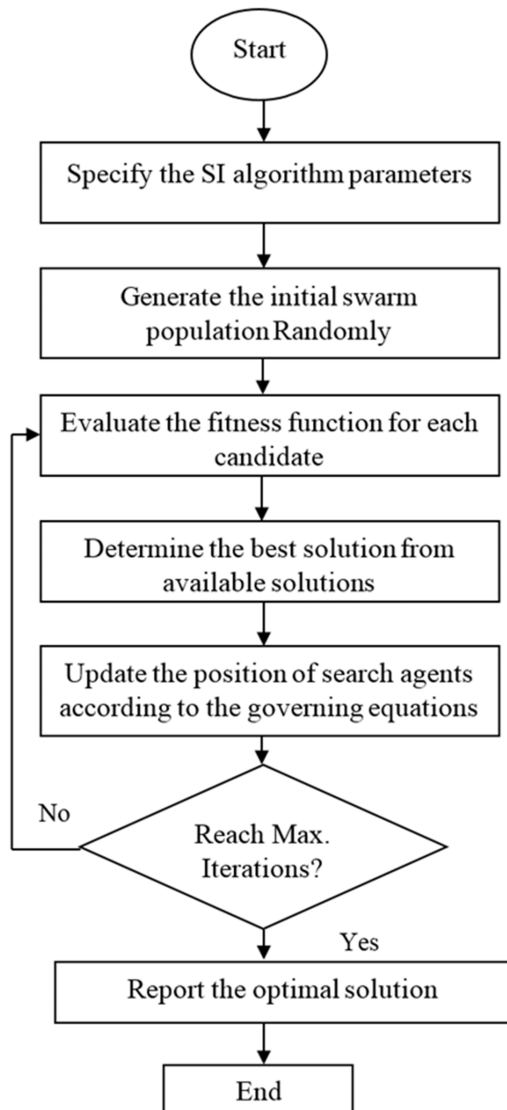
FIGURE 6. A generalized flowchart of swarm intelligence techniques for obtaining the optimal solution.

FIGURE 7. Standard PSO flowchart [106].

ahead of its application. These parameters generally include algorithm constants and other optimization related variables like; the number of iterations, swarm size (number of particles), number of variables to be optimized, etc., required for smooth execution of the optimization program code. Following this, a fitness function is defined which needs to be minimized or maximized according to the provided constraints. The optimization algorithm evaluates and updates the fitness function of each of the particles and finds the best solution amongst all the workable solutions during each iteration. Further, based on the results, the best combination of particles (variables) is chosen which satisfies the stated constraints and fitness function. Finally, the iterative process stops once the algorithm completes the maximum number of iterations or when it attains a suitable fitness value pre-decided by the programmer.
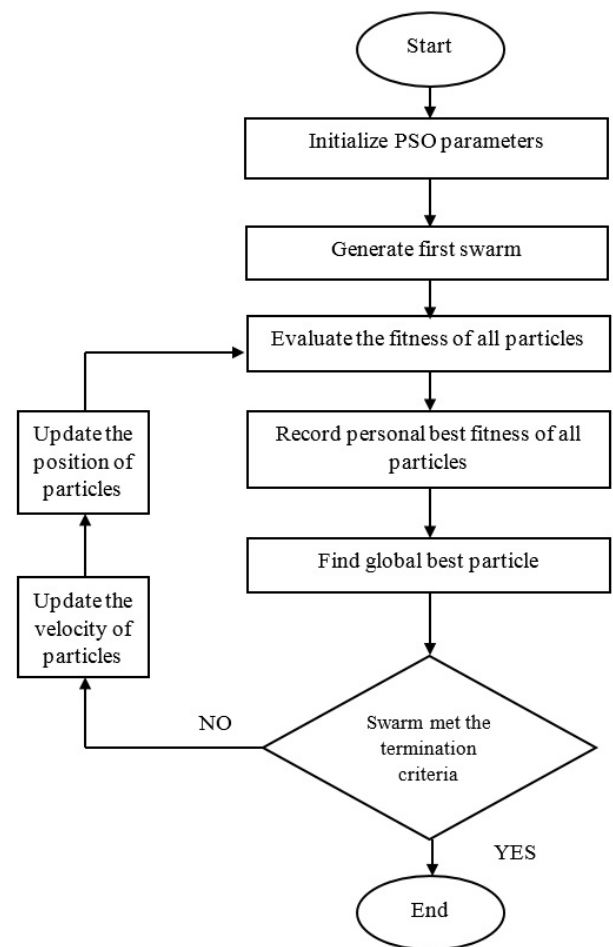
It may be noted that there are several optimization algorithms available in literature but all may not be suitable for optimizing a particular system [100]. Therefore, the choice of an appropriate optimization algorithm for solving a particular optimization problem is also another vital issue in this regard. In addition, it is important to note that all SI algorithms are problem specific and no SI algorithm is equally good for all optimization problems. One more important point which need to be considered while using any SI based optimization method is that, all the SI-based algorithms are stochastic in nature and their very basic operation is based on generation of random numbers during their initial phase of code execution. Hence, in order to obtain the statistical data from such algorithms, the same is needed to be simulated for at-least 10 to 50 times depends on the time consumed per simulation run and solution quality required.

VI. PARTICLE SWARM OPTIMIZATION FOR DYNAMIC RESPONSE AND POWER QUALITY ENHANCEMENT OF AC MGs

The PSO is one of the most widely used metaheuristic optimization techniques in power quality enhancement and
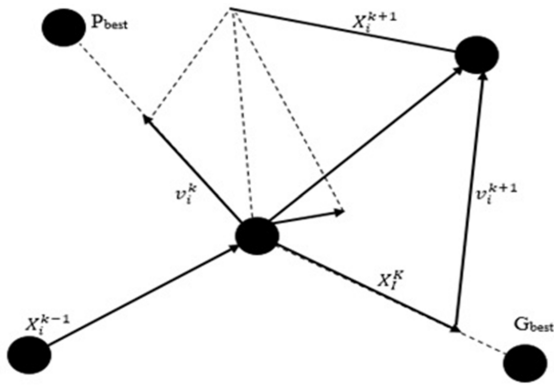
FIGURE 8. Movement of particles in PSO.

voltage-frequency control of the AC MGs. The advantages of PSO over Genetic algorithm (GA) includes its easier implementation with comparatively less number of tuning parameters, its effective memory capability, and efficiency in maintaining the diversity of the swarm [101]. Furthermore, unlike GA, PSO does not possess complex evolution operatives such as crossover and mutation [102] as well as it does not impose a significant computational burden on the microcontroller [103]. This algorithm was proposed by Kennedy and Eberhart in 1995 [104]. It is basically an evolutionary computational technique that pretends the social conduct of the swarm of birds or bees in nature when they search for food in a field. In technical terms, PSO is defined as an iterative algorithm that searches for the space to arrive at an optimal solution for a given objective function [105]. As such, it iteratively tries to enhance a particle solution with respect to a given measure of reference. These particles move in a defined search-space to update its velocity and position according to two simple mathematical relationships given in Equation 1 and 2. Every particle is inclined by its own best position (local best) and the neighborhood's best position (global best). A flowchart representing the complete operating mechanism of PSO is shown in Figure 7 while the basic movement of search agents is illustrated in Figure 8.

The moving behavior of the particles as depicted in Figure 8, can be mathematically expressed by equating the velocity and the position of the individual particle as provided in Equation 1 and 2 respectively.

$$v_i^{k+1} = w v_i^k + c_1 r_1 (P_{best} - X_i^k) + c_2 r_2 (G_{best} - X_i^k) \quad (1)$$
$$X_i^{k+1} = X_i^k + v_i^{k+1} \quad (2)$$

where v_i represent the initial velocity component and X_i^k represents the position of the k_{th} particle during i_{th} iteration. In Equation 1, w is the inertia weight; c_1 and c_2 are the acceleration constants, while P_{best} is the personal best position and G_{best} is the global best position.

A substantial amount of work has been undertaken in the recent past to enhance the power quality and control of MGs using PSO. Moghimi *et al.* [16] explored PSO for regulating the voltage and frequency of the DG units in an islanded

MG. The power controller parameters (Kp and Ki) were optimized by using the mentioned algorithm in order to obtain the optimal values of the controlled variables for regulating voltage, frequency, active power and reactive power of the studied MG system. Vinayagam *et al.* [18] developed an intelligent controller based on the PSO algorithm for the voltage, frequency and power regulation in an islanded MG. The performance of the developed controller was tested under load and source (solar irradiance of PV) change conditions. The cost function for the PSO was chosen as Integral square error (ISE) with penalty function. The proposed control strategy successfully reduced the variations in frequency, reactive power (from 26.5-30 kVAR to 19.5-20 kVAR) and settling time (from 1.35s to 0.24s). However, the value of the virtual resistor used in the control circuit was selected by "hit and trial" method which is a time-consuming process and does not ensure the optimal selection. García-Triviño *et al.* [38] evaluated and compared three PSO based PI control strategies for grid-tied MG inverters. The simulations were performed to test the effectiveness of proposed control strategies under different reference values for active and reactive power. The outcomes of the research work prove that the online PSO-based PI controller with a cost function of Integral time absolute error (ITAE) attains a better dynamic response as compared to other methods at identical operating conditions. In another study [39] an optimal PSO based power flow controller was designed for the grid-connected MG with the objective of controlling power flow between utility and MG. In this case, the PSO was used to select the optimal values of two PI controllers used in the power control loop of the MG controller. Qiao *et al.* [41] presented the optimal tuning of PI controller gains using PSO for the rotor-side converter of grid-connected Doubly-fed induction generators (DFIG). The key objective of the study was to minimize the over-current in the rotor circuit during grid faults. Althobaiti *et al.* [42] used PSO to obtain the optimal values for adaptive controller containing PI and proportional resonant (PR) controllers in three-phase grid-connected MG. The major objective of the research work was to improve the transient response of the studied MG system during a temporary voltage sag from 90% to 10% for around 1.98s. Furthermore, the harmonic contents were reduced up to 0.59% along with higher PV penetration. Ray *et al.* [43] presented a method for the voltage harmonics elimination using PSO based controlled PWM DG inverter. Furthermore, for the removal of 5th, 7th, 11th, and 13th harmonics from voltage waveform, the PSO based Selective harmonic elimination (SHE) method was used. In another study [44], the authors have developed PSO based controller to explore eight different optimal parameters of the PV based MG. Three distinct time-domain cost functions were formed to assess the performance of PI controllers under different solar irradiance conditions. The objective of the study was to enhance the transient and steady state response over the wide range of solar irradiance conditions. Al-Saedi *et al.* [45] presented a real-time self-tuning optimization method using PSO for optimizing the parameters of the current controller

TABLE 2. PSO for dynamic response & power quality enhancement of AC MG.

Ref.	Objective of the Study	DGs Used	MG Operating Mode	Studies Operating Conditions
[14]	Voltage and frequency regulation and dynamic response enhancement	-	Islanded	Step load change
[15]	Regulating voltage-frequency and reactive power compensation	-	Islanded	Load variations
[16]	Voltage and frequency regulation	-	Islanded	Load variations and sudden fluctuations
[17]	Voltage and frequency regulation	-	Islanded	Load variations
[18]	Power quality and frequency control	Solar PV	Islanded	Source and load variations
[38]	Active and reactive power regulation	Wind PV and Fule cell	Grid-connected	Load variations
[39]	Regulating active and reactive power flow and power sharing between grid and utility	-	Grid - connected	Load variations
[40]	Active and reactive power control	Real time Digital Simulator	Grid - connected	Load changes
[41]	DC link voltage and frequency regulation	Wind Turbine	Grid - connected	Grid fault
[42]	To overcome harmonics and unbalances in voltage	Solar PV	Grid - connected	Source change
[43]	Voltage harmonics elimination	Fuel cell and Wind turbine	Grid - connected	Distorted output voltage waveform
[44]	Transient response improvement (Overshoot and settling time)	Solar PV	Grid - connected	Source changes
[45]	Minimize current harmonics	Solar PV	Grid - connected	Load changes
[51]	Power factor improvement and harmonic mitigation	PV, Fuel cell, Micro turbine, Wind, Diesel	Both	Utility grid outage and load variations
[52]	Voltage stability improvement	Wind-PV	Both	Large voltage disturbances
[54]	Active and reactive power control	-	Both	Load variations
[53]	Voltage, frequency , active and reactive power regulation	-	Both	Load variations
[55]	Optimal design of LC filter, Damping resistance, power-sharing	-	Both	Load variations and Fault condition

in a grid-connected PV system. The objective of the study was to attain the enhanced dynamic response for the inverter's output current with reasonable harmonics level in steady-state condition. Another study [51], also used PSO to optimize the control gains of D-FACTS controllers to attain the high dynamic performance and to accomplish the smooth integration of DERs in an AC MG. PSO based controller was designed in [52] to optimize the control gains of different converters simultaneously in order to rapidly stabilize and restore the voltage of both DC and AC parts of a hybrid AC-DC MG under the different disturbances. In another study, Chung *et al.* [53] used PSO for tuning power and current control loop parameters in both islanded and grid-tied modes of MG's operation. The focus of the study was to improve the transient response and to control the voltage and frequency for both grid-connected and islanded modes of MG under abrupt load changes. Furthermore, the authors have extended their work in reference [54] and optimized gains of two identical PI controllers along with droop coefficients with the same algorithm. The aim of the study was to enhance the power-sharing performance and ensure stable operation under the abrupt load changes in the grid-connected MG system. Hassan and Abido [55] considered LC filter design, controller parameter selection, and damping resistance value as the optimization variables in the grid-connected mode of operation,

while power-sharing coefficients and PI controller gains were optimized for the islanded mode of operation. The PSO was used to select the optimal values of the considered parameters for both cases. Two major limitations of this research work were found as; (i) the model was only studied for grid forming configuration and (ii) large settling time (1-2 s) was observed in output active and reactive power curves due to the non-adaptiveness of PSO. The authors extended their work in [107] where they implemented a Real-Time Digital Simulator (RTDS) practically for optimizing the dynamic response of the studied MG system. The simulated and experimental results were successfully obtained; however, the experimental setup was made only for a very small power injection level (5 kW). PSO had also been used in [108] to optimally size and allocates multiple STATCOM units to regulate the voltage profile of AC MG system. The results of the study confirmed that the optimal sizing and placement decided by PSO has reduced the power losses by 20% and regulated the voltage up to ±5% at each bus. In [109], STATCOM was applied for controlling reactive power as per load demand, and PSO was chosen to tune a STATCOM's PI controller in order to attain an optimal dynamic response. In addition, the settling time was also reduced from 0.16s to 0.1s when compared to conventional methods. In [110], some specific low order harmonics were minimized in different multilevel inverter

topologies by using an advanced version of the PSO. In order to establish the effectiveness of the presented control strategy, the obtained results were compared with that of sequential quadratic programming and continuous GA under identical operating conditions. The authors in [111] have demonstrated an efficient gain-scheduling and PI tuning method using PSO to achieve the required system performance and power quality during abnormal cases such as faults or islanding. The tuning of the current and power loop PI controllers was performed using PSO in order to obtain stable operation under the studied conditions.

Although, the PSO algorithm has been found very effective in obtaining the optimal response in various studies, however, there are some serious limitations pertaining to PSO which essentially needs to be addressed. Some of these limitations include its low convergence rate in the iterative process, trapping into a local minimum in high-dimensional space, and uncertainty in its parameter selection [112], [113]. The PSO algorithm performs reasonably well in the early iterations but finds snags in attaining an optimal solution in few of the benchmark functions [114].

A brief summary of the PSO based controllers reported in the literature for dynamic response and power quality enhancement of the islanded and grid-tied MGs along with their research objectives, MG operating mode and type of DGs utilized is depicted in Table 2.

A. IMPROVED VERSIONS OF PSO

Maintenance of a suitable balance between the global and the local searching capability throughout the iterative process is critical to the success of an evolutionary algorithm [115]. In PSO, the inertia weight (ω) and the acceleration coefficients (c_1 and c_2) are used to achieve the mentioned objectives. During the exploration phase, PSO requires a large value of inertia weight while a small value of the same parameter is required during the exploitation. As such, by suitably varying the inertia weight dynamically during the PSO searching process, its searchability can be efficiently enhanced. Since the searching process of the PSO is non-linear and random in nature, therefore, it is very difficult to exactly model and adjusts the inertia weight dynamically. However, by linearly decreasing the inertia weight from a relatively larger value to a smaller value through the course of PSO run, the algorithm's global searching ability at the beginning of the run and the local search ability near the end of the run can be efficiently enhanced. In addition to the inertia weight updating, the acceleration coefficients are also required to be updated during the complete iterative process in order to get large cognitive and small social parameter values at the beginning and vice versa at the end of the search process. The mentioned settings of c_1 and c_2 are made so that the particles are allowed to move around a wider search space at the beginning while those are allowed to converge to the global optima in the latter part of the search process [116]. Several studies [117]–[119] have attempted to dynamically adjust these parameters to achieve the mentioned

TABLE 3. The selected parameter for PSO for power quality enhancement of MG.

Reference	PSO Constants		
	ω	c_1	c_2
[15]	0.05-0.5	0.09-0.1	0.09-0.1
[17]	0.05-0.5	0.09-0.1	0.09-0.1
[45]	0.9	2.0	2.0
[51]	0.9-0.4	2.0	2.0
[52]	0.9-0.4	2.0	2.0
[54]	1	2.0	2.0
[53]	1	2.0	2.0
[55]	1	2.0	2.0
[105]	0.9-0.4	2.0	2.0
[121]	0.05-0.5	0.09-0.1	0.09-0.1
[122]	1	1.0	1.0
[123]	0.4-0.9	1.0	1.0

characteristics of the PSO for obtaining an optimal solution of the studied optimization problem. In [120], the authors have extensively reviewed the literature to address the convergence behaviors of 18 different self-adaptive PSO algorithms both empirically and analytically. However, in the majority of the PSO based MG controllers, these parameters are chosen as constant values throughout the simulation time as shown in Table 3. Nevertheless, some prominent research studies have considered adaptive or modified PSO based controllers for MG controls which have been considered for the review purpose in current study.

Saad *et al.* [19] developed an improved PSO (IPSO) to tune the parameters of a master controller in a hybrid MG. The developed controller was used to regulate the output power from three different DGs. The purpose of implementing IPSO in the controller was to manage the optimal power flow between MGs under different load and source conditions. An online intelligent Fuzzy logic-PSO based controller was developed in [20] for optimally tuning the PI-based controller in order to regulate the frequency in an AC MG. In order to establish the superiority of the proposed controller, its performance was compared with the conventional Z-N PI, and fuzzy PI designed control approaches. In another study, Multi-objective PSO (MOPSO) technique was used by Sharaf and El-Gammal [21] for finding the optimal control parameter settings to minimize the global dynamic error in an islanded MG. Furthermore, the MOPSO technique was also used in [22] to achieve the optimal control parameters for the PWM triggering block which dynamically minimizes the global dynamic error in different components like Space Vector Pulse Width Modulator (SVPWM), motor and the switched filters. In another study [46], MOPSO was programmed to tune the PI controller parameters in grid-connected MG. The goal of the study was to achieve multiple objectives such as optimal control of rectifier converter, dynamic filter compensation, optimal power filter parameters using real-time dynamic and self-regulating error tracking.

It is evident from this brief review on the PSO algorithm that various studies sufficiently established the effectiveness of the self-adaptive PSO concept over the conventional one in its exploration, exploitation, and convergence profiles. However, due to the non-linear searching process of the PSO,

TABLE 4. Modern SI techniques for power quality enhancement of AC MGs.

Ref.	SI Optimization Techniques	Objective	DGs Used	MG Operating Mode	Studies Operating Conditions
[23]	HBB-BC	Voltage regulation	-	Islanded	Load variations
[24]	GOA	Voltage and frequency control	Solar PV	Islanded	Load variations
[25]	Human Brain Emotional Learning Algorithm (HBELA)	Frequency control	PV, Wind Diesel and Fuel cell	Islanded	Load variations
[26]	Pareto-based Big Bang-Big Crunch (BB-BC) algorithm	Voltage and frequency regulation	-	Islanded	Load variations
[27]	FOA	Voltage and frequency control	PV-Wind	Islanded	Load variations
[28]	FOA	Frequency Control	PV-Wind	Islanded	Load variations
[29]	FL and Seeker Optimization	optimal power-sharing between micro-sources	PV and Fuel cell	Islanded	Load variations and fault conditions
[30]	Immune Algorithm	Frequency control	Wind-Diesel	Islanded	Load and source variations
[31]	Social-spider optimization	Frequency control	Wind, PV and Diesel	Islanded	Load and source variations
[32]	Moth-Flame Optimization Algorithm	Frequency control	PV, Fuel cell, Diesel and Electrolyser	Islanded	Load and source variations
[33]	Krill Herd Algorithm	Frequency control	Wind-Diesel	Islanded	Load and source variations
[34]	Interior Search Algorithm	Frequency control	Wind-Diesel	Islanded	Load and source variations
[35]	Whales Optimization Algorithm (WOA)	Voltage and frequency control	Solar PV	Islanded	Load variations
[36]	WAO	Voltage and frequency control	Fuel cell	Islanded	Load variations
[37]	SSA	Voltage and frequency control	Solar PV	Islanded	Load variations
[47]	SSA	Active and reactive power regulation	Solar PV	Grid-connected	Load variations
[48]	FOA	Frequency control	PV-Wind	Grid-connected	Load variations and Fault condition
[49]	Improved BFO	Extraction of maximum power from the wind turbine	Wind Turbine	Grid-connected	Source variations
[50]	Grasshopper Optimization Algorithm (GOA)	Power flow regulation	Solar PV	Grid-connected	Load variations
[56]	ABC	Active and reactive power regulation	PV and Fuel cell	Both	Load variations

it is very difficult to dynamically adjust the PSO parameters (ω, c_1, and c_2) accurately. Furthermore, programming the controller based on self-adaptive PSO is complex when compared to the conventional PSO.

VII. MODERN SI-BASED OPTIMIZATION TECHNIQUES IN POWER QUALITY ENHANCEMENT OF AC MGs

This section provides a review of the modern SI-based optimization techniques used for the dynamic response and power quality enhancement of AC MGs.

The Hybrid Big Bang-Big Crunch (HBB-BC) algorithm based controller was designed to regulate the MG voltage profile in [23]. The results obtained were compared with that of the PSO and Big Bang-Big Crunch (BB-BC) algorithms for the same system configuration and optimization problem. However, the frequency control was not adopted for the studied system and hence frequency settled to a lower value (59.7 Hz) than the reference after a small load change. Furthermore, the feed-forward gains and droop coefficients were selected manually by the "trial and error" method and hence do not ensures the optimal selection of mentioned parameters. In another study [48], the Firefly optimization algorithm (FOA) was designed and simulated for optimal tuning of PI controllers in a grid-tied hybrid Wind/PV generation system. The objective of the study was to regulate the voltage at the PCC and system frequency in both load changing and fault conditions. Saad *et al.* [49] presented an improved Bacterial

foraging optimization (BFO) algorithm for regulating the active and reactive current components of the grid-connected wind generator. The objective of the study was to supply the regulated active and reactive power to the grid at both normal and fault conditions. In another study [56], the Artificial bee colony (ABC) algorithm was used to tune the PI parameters for regulating active and reactive power in an AC MG. Droop control was adopted for controlling the voltage and frequency deviations in both islanded and grid connected mode of operation. Furthermore, to obtain the optimal dynamic response of the studied MG system, the power and the current controller parameters were optimized by using ABC optimization algorithm. Dasgupta *et al.* [124] have designed a Spatial iterative learning controller (ILC) for regulating the grid voltage in a grid-connected PV system. The proposed controller was used to maintain the required voltage at the load side and eliminating the grid harmonics. Banerjee *et al.* [125] have developed the Seeker optimization algorithm (SOA) based controller to regulate the reactive power of an MG comprising of wind and diesel power generators. The authors have further extended their work and proposed an online reactive power compensation method for wind and diesel generator based islanded MG in [126]. The tunable variables of the studied model were optimized by the Opposition-based gravitational search algorithm (OGSA). Mallesham *et al.* [127] adopted an organized method for tuning of PI controller parameters, droop coefficients, and frequency bias in an islanded MG

TABLE 5. Performance evaluation of PI controllers in AC MG controls.

Ref.	Technique	No. of Particle	No. of Iteration	No. of Iterations optimal value	Fitness Function	No. of Dimensions	Final fitness Value
[15]	PSO	50	50	4	Min ITAE	4	0.8e-4
[17]	PSO	50	50	11	Min ITAE	4	9.56e-5
[18]	PSO	50	70	29	Min ISE	4	56.5
[23]	HBB-BC	20	10	5	Min ITAE	4	0.1496
[24]	GOA	50	100	16	Min ITAE	4	0.4963
[25]	HBELA	-	-	-	Min ITAE	2	4.5398e3
[26]	Pareto-based BB-BC	20	10	1	Max $S_u = (\Pi_{j=1} Ma_j)^{\frac{1}{M}}$	4	1.591e-6
[28]	FOA	50	-	-	Min ITAE, ISE, IAE	15	0.3297
[35]	WOA	50	100	32	Min ITAE	4	0.1e-4
[37]	SSA	50	50	17	Min ITAE	5	0.5841
[39]	PSO	50	50	5	Min ITAE	4	0.2e-4
[42]	PSO	-	20	8	Min ITAE	8	0.11
[47]	SSA	50	50	09	Min ITAE	5	0.6963
[48]	FOA	100	2000	280	Min ISE	4	-3.7e-3
[51]	PSO	50	200	40	Min $(\alpha_1 J_1 + \alpha_2 J_2)$	6	0.03
[54]	PSO	10	200	9	Min (J1+J2)	6	3.6766
[53]	PSO	10	600	280	Min ITAE	6	19.54
[55]	PSO	20	100	16	Min $\delta(P)^2$	6	1000
[56]	ABC	80	60	24	Min IAE	8	1.05e6
[129]	Fuzzy Fractional-order PSO	30	300	40	Min ISE	7	4.51

comprising a diesel generator, fuel cell, and the battery. Different AI techniques like, GA, PSO and BFO algorithm were tested for optimal tuning of various parameters in an nonlinear AC MG. It was found that the BFO based controller has provided the most optimal dynamic response of the studied system as compared to the other algorithms under same MG operating conditions. Chaiyatham and Ngamroo [128] presented Bee colony optimization (BCO) based optimal FL PID controller for stability enhancement and minimizing the power fluctuations in an islanded MG. BCO was used to tune the rules for the FL based PID controller. Some of the prominent studies in this research area, undertaken by the researchers from different parts of the world, are presented in Table 4.

This review of popular and modern SI based optimization algorithms is indicative of the importance of selecting a suitable optimization algorithm for the defined optimization problem in order to achieve minimization or maximization of a particular fitness function. Furthermore, most of the modern MG control architectures used PI controllers for maintaining voltage, frequency, active and reactive power and the most commonly used objective functions are ITAE and ISE. The mentioned SI techniques in Table 4 are required to minimize the stated FF in a minimum amount of time and iterations in order to get the optimal dynamic response of the studied AC MGs. Table 5 depicts the references in which the PI controller parameters were optimized for minimization or maximization of a particular FF along with their final fitness value, number of iterations and the total number of particles.

In [26] of the Table 5, S_u and M represent the fitness function obtained from the combination of fuzzy memberships and the number of objective functions, respectively. It is pertinent to mention that for any optimization algorithm, the greater the convergence rate, the lower the number of

iterations it takes to reach the final fitness value optimally. The convergence rate generally decides the efficiency of an optimization algorithm. As such, the greater the convergence rate, the greater would be the efficiency of an optimization algorithm in finding the optimal solution to a particular problem. It is, therefore, highly desirable to have a higher convergence rate during the iterative process with nearly zero steady-state error.

VIII. CONCLUSION AND FUTURE OUTLOOK

This paper has reviewed the application of the SI-based optimization techniques for the dynamic response and power quality enhancement of AC MGs. The work is anticipated to be useful for the researchers and experts working on newly developed SI algorithms as applied to AC MG control architectures. A total of 43 related publications were reviewed for around 15 SI optimization techniques with a detailed review of one of the basic and most widely used SI based metaheuristic techniques called PSO in order to have a better and wider understanding of the stated area of research. Based on the reviewed articles it is established that the SI optimization-based controllers have led new and intelligent ways of optimizing MG dynamic response and power quality. However, each of the discussed SI algorithms has certain limitations that need to be addressed before employing it for solving the optimization problem. Since all the SI algorithms are problem specific and no algorithm is equally good for all optimization problems, hence it is not possible to predict the superiority of any SI based optimization method over the other in general. Furthermore, since all the SI-based algorithms are stochastic in nature and their very basic operation is based on generation of random numbers during their initial phase of code execution. Therefore, in order to obtain the statistical data from such algorithms, the algorithm is needed to be simulated for at-least 10 to 50 times depends on the time

consumed per simulation run. The fitness function, which is required to be minimized or maximized is also an important factor in the selection of a proper SI optimization algorithm for the specific application. The two of the most important parameters for examining the effectiveness of an optimization technique in optimizing a given fitness function are; suitable convergence rate and a proper balance between the exploration and exploitation capability throughout the iterative process. Based on this review, it is envisaged that the modern SI methods with high exploration and exploitation balancing capability, can be effectively employed to improve the power quality and transient response of MG systems in both islanded and grid-tied modes of its operation. These capabilities of optimization techniques are very desirable while considering a rapidly increasing penetration of renewable energy sources into the existing power system which is one of the growing trends of the present era.

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