A Hybrid Quantum Inspired Particle Swarm Optimization and Least Square Framework for Real-time Harmonic Estimation

Abu Bakar Waqas, Muhammad Mansoor Ashraf, and Yasir Saifullah

***Abstract*—The power quality is becoming an extensively addressing aspect of the power system because of the sensitive operation of the smart grid, awareness of power quality, and the equipment of modern power systems. In this paper, we have conceived a new hybrid Quantum inspired particle swarm optimization and least square (QPSO-LS) framework for real-time estimation of harmonics presented in time-varying noisy power signals. The technique has strong, robust, and reliable search capability with powerful convergence properties. The proposed approach is applied to various test systems at different signal to noise ratio (SNR) levels in the presence of uniform and Gaussian noise. The results are presented in terms of precision, computation time, and convergence characteristics. The computation time decreases by 3-5 times as compared to the existing algorithms. The technique is further authenticated by estimating harmonics of real-time current or voltage waveforms, obtained from light emitting diode (LED) lamp and axial flux permanent magnet synchronous generator (AFPMSG). The results demonstrate the superiority of QPSO-LS over other methods such as LS-based genetic algorithm (GA), particle swarm optimization (PSO), bacterial foraging optimization (BFO), artificial bee colony (ABC), and biogeography based optimization with recursive LS (BBO-RLS) algorithms, in terms of providing satisfactory solutions with a significant amount of robustness and computation efficiency.**

***Index Terms*—Harmonic estimation, power quality, particle swarm optimization (PSO), least square (LS), smart grid.**

I. Introduction

WITH the development of modern power systems, it has become easy to improve the performance of the system due to the utilization of advanced communication and monitoring technology [1]. However, due to the extensive usage of nonlinear power electronic devices, sensitive loads, advanced metering, sensing, and control mechanisms, the performance of the smart grid downgrades significantly, and the power quality deteriorates [2], [3]. Therefore, it is essential to develop fast, less complicated, and more efficient methods to evaluate power quality by detecting and mitigating the harmonics augmented in power waveforms [4]. Accurate estimation of harmonics can help us design efficient compensators and filters to counteract the problems caused by nonlinear devices and loads [5], [6].

Nowadays, meta-heuristic algorithms are gaining immense attention and are widely presented in the literature to deal with power system problems such as electrical load forecasting [7], least-cost economic emission dispatch in the presence of renewable energy sources [8], and least cost generation expansion planning [9]. Reference [10] proposed a new hybrid meta-heuristic algorithm based on particle swarm optimization (PSO), and bacterial foraging to optimize the Takagi-Sugeno fuzzy controller to detect the control signal in a wide-area power system.

Similarly, time-varying harmonics and non-stationary signals had paved the path for researchers to apply intelligent and self-adaptable nature-inspired heuristic algorithms to estimate harmonics in slanted waveforms [11], [12]. Moreover, heuristic algorithms were often hybridized with statistical approaches to obtain accurate estimations of harmonics [13], [14]. Reference [15] utilized a hybrid least square (LS) based fuzzy bacterial foraging (FBF) approach for harmonic estimation. LS was used for the evaluation of amplitudes, whereas FBF was modified to estimate the phases of harmonics. Reference [16] established an optimal power system harmonics estimator using particle swarm (PS) optimizer. PSO with a passive congregation (PSOPC) was hybridized with LS to efficiently investigate both the nonlinear phases and linear amplitudes of harmonics. Reference [17] proposed hybrid Adaline and bacterial foraging optimization (BFO) to correctly estimate the phases and amplitudes of integer-, inter-, and sub-harmonics. BFO strategy was made adaptive by updating the weights of Adaline taking initial weights as outputs of BFO. Reference [18] incorporated a hybrid adaptive bacterial swarm framework to estimate the integer-, inter-, and sub-harmonics. Due to its inherent capability of dealing with multi-modal problems, BFO was exploited to deal with the estimation of nonlinear phases of harmonics, whereas the amplitudes were estimated using LS. References [11] and [19] presented hybrid firefly algorithm based LS (FA-LS), and hybrid firefly algorithm based recursive LS (FA-RLS)

Manuscript received: February 19, 2019; accepted: November 12, 2019. Date of CrossCheck: November 12, 2019. Date of online publication: June 29, 2020.

A. B. Waqas (corresponding author) and Y. Saifullah are with the Department of Communication Science and Engineering, School of Information Science and Technology, Fudan University, Shanghai 200433, China (e-mail: bwabu18@fudan.edu.cn; suyasir17@fudan.edu.cn).

M. M. Ashraf is with the Electrical Engineering Department, University of Engineering and Technology, Taxila 47050, Pakistan (e-mail: mansoor.ashraf@uettaxila.edu.pk).

DOI: 10.35833/MPCE.2019.000098

methods to adequately estimate the contents of harmonics in slanted power signals. And firefly was integrated to develop weights for RLS in successive iterations since it requires prior knowledge to update the data. A real-time distorted signal from solar connected inverter was enlisted to test the usefulness of the proposed algorithm. The authors discussed the effectiveness of the proposed approach in a way that firefly is a much better heuristic algorithm compared to other similar algorithms. However, in these studies, classical computation methods were used to estimate the amplitudes and phases of harmonics.

With the conception of quantum information, researchers focus on quantum computation and estimation [20], [21]. In this paper, we have proposed a new Quantum inspired particle swarm optimization and LS (QPSO-LS) algorithm for the analysis of harmonics due to less computation parameters and easy implementation. More explicitly, the contributions of this paper are as follows.

1) The development and maiden application of the proposed QPSO-LS algorithm for the estimation of harmonics, including fundamental, integer-, inter-, and sub-harmonics of noisy power signals with different dimensions.

2) Best estimator is searched by giving a comparative performance evaluation of the proposed algorithm with other hybrid algorithms. The comparison is drawn in tabulated form in Section IV.

3) The estimation of harmonic parameters on the real-time data obtained from axial flux permanent magnet generator (AFPMG) setup and light emitting diode (LED) lamp is applied to evaluate the performance of the algorithm.

The rest of this paper is organized as follows. Section II gives the mathematical modeling of the harmonic estimation problem. Section III explains the algorithm and the proposed approach. In Section IV, the results are discussed, and Section V concludes the paper.

II. Problem Formulation for Estimation of Power System Harmonics

Successive approximation of harmonics for power signals constitutes two components: linear estimation of amplitudes and nonlinear estimation of phases. The time-varying nature of power signals makes harmonic estimation a very cumbersome problem, so it requires proficient and robust algorithms. Mathematically, a signal can be modeled as the sum of sine or cosine functions with higher-order frequencies given by:

$$S(t)=\sum_{h=1}^{H} K_h \sin\left(\omega_h t+\phi_h\right)+K_{dc}\exp\left(-\gamma_{dc}t\right) \tag{1}$$

where H is the total number of harmonic order; h is the number of harmonics order; K_h is the amplitude of harmonic; ω_h is the angular frequency of higher-order harmonics; ϕ_h is the phase of harmonics; and $K_{dc}\exp(-\gamma_{dc}t)$ is DC decreasing offset. It might be possible that the signal $S(t)$ is corrupted with additive random noise N_t, so the complete model of the signal can be described as:

$$S(t)=\sum_{h=1}^{H} K_h \sin\left(\omega_h t+\phi_h\right)+K_{dc}\exp\left(-\gamma_{dc}t\right)+N_t \tag{2}$$

The processing of the signal becomes easy if it is available in a discrete form. Hence the digital version of the above signal is given by:

$$S\left(mT_s\right)=\sum_{h=1}^{H}\left(K_h \sin\left(\omega_h mT_s+\phi_h\right)+K_{dc}\exp\left(-\gamma_{dc}mT_s\right)+N_{mT_s}\right) \tag{3}$$

where T_s and m are the sampling time and sample number, respectively. By using the trigonometric identity, the signal can be rewritten as:

$$S[m]=\sum_{h=1}^{H}\left(K_h \sin\left(\omega_h mT_s\right)\cos\left(\phi_h\right)+K_h\cos\left(\omega_h mT_s\right)\sin\left(\phi_h\right)\right)+ K_{dc}\exp\left(-\gamma_{dc}mT_s\right)+N_m \tag{4}$$

Further, the decaying DC term can be expanded by applying the Taylor series, and after ignoring the higher-order terms, the signal can be described by:

$$S[m]=\sum_{h=1}^{H}\left(K_h \sin\left(\omega_h mT_s\right)\cos\left(\phi_h\right)+K_h\cos\left(\omega_h mT_s\right)\sin\left(\phi_h\right)\right)+ K_{dc}-K_{dc}\gamma_{dc}mT_s+N_m \tag{5}$$

The equation which is to be estimated can be written in the following parametric form:

$$\hat{S}[m]=\boldsymbol{X}\left(\boldsymbol{H}(m)\right)^{\mathrm{T}} \tag{6}$$

where $\hat{S}$ is an estimated signal in discrete form; $\boldsymbol{X}$ is a vector of an unknown parameter which has to be updated using the algorithm for optimal estimation of harmonics; and $\boldsymbol{H}$ is a discrete vector of known values derived from the given harmonic frequencies. More explicitly, the vectors $\boldsymbol{X}$ and $\boldsymbol{H}$ are described as:

$$\boldsymbol{X}=\left[K_1\cos(\phi_1)\quad K_1\sin(\phi_1)\quad \ldots \quad K_h\cos(\phi_h)\quad K_h\sin(\phi_h)\quad K_{dc}\quad K_{dc}\gamma_{dc}\quad 1\right] \tag{7}$$

$$\boldsymbol{H}(m)=\left[\sin\left(\omega_1 mT_s\right)\quad \cos\left(\omega_1 mT\right)\quad \ldots \quad \sin\left(\omega_h mT_s\right)\quad \cos\left(\omega_h mT\right)\quad 1-mT_s\ N_m\right] \tag{8}$$

where T is the number of iterations.

Once the unknown parameter vector is updated using QPSO, the amplitudes and phases of fundamental and the h^{th} harmonics are calculated as:

$$K_h=\sqrt{\phi_{2h}^2+\phi_{2h-1}^2} \tag{9}$$

$$\phi_h=\arctan\left(\frac{\phi_{2h}}{\phi_{2h-1}}\right) \tag{10}$$

If the signal has a DC decaying component, the parameters are computed by the expressions given by:

$$K_{dc}=\phi_{2h+1} \tag{11}$$

$$\gamma_{dc}=\frac{\phi_{2h+2}}{\phi_{2h+1}} \tag{12}$$

III. QPSO Algorithm and Proposed Approach

The QPSO algorithm proposed and developed in [22] is an efficient form of PSO in the quantum domain. The selection of self-adaptive probability and mutation of chaotic sequence, due to its searchability and quicker convergence speed, make the QPSO an attractive candidate for optimization problems. Quantum bit and angle are used to represent the state of a particle instead of position and velocity. A qubit is a superposition of two different quantum states, $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ with complex numbers α and β satisfying $|\alpha|^2 + |\beta|^2=1$. This quantum state makes the algorithm simple and easy to implement with fast convergence and less computation time. The algorithm and the proposed approach are described in the following lines.

Assume that the N dimension of quantum space has a population, which consists of M particles. The location of the j^{th} particle is $\boldsymbol{U}_j=[u_{j1}, u_{j2}, \ldots, u_{jN}]$, and $\boldsymbol{X}_{local}=[x_{j1}, x_{j2}, \ldots, x_{jN}]$ is the particle with the best location. After all the particles, the global best position is represented as $\boldsymbol{X}_{global}=[x_{g1}, x_{g2}, \ldots, x_{gN}]$.

The position of the j^{th} particle in the n^{th} dimension, while it gets through stochastic simulation of Monte Carlo measurement, is defined as:

$$u_{jn}=x_{jn}\pm\frac{k}{2}\ln\left(\frac{1}{r}\right) \tag{13}$$

where $j=1,2,...,M$ is the particle number; $n=1,2,...,N$ is the dimension of the problem; r is the random number in the range of $[0,1]$; and k is obtained by the current position of the particle, whereas the best location is $k=2\Omega\left|x_{jn}-u_{jn}\right|$, and Ω is the contraction expansion factor. Thus, we can write the updated equation as:

$$u_{jn}(t+1)=x_{jn}\pm\Omega\left|x_{jn}-u_{jn}(t)\right|\ln\left(\frac{1}{r}\right) \tag{14}$$

To avoid premature convergence, a parameter in the algorithm is calculated as:

$$Y_{best}=\frac{1}{M}\sum_{j=1}^{M}\boldsymbol{X}_j(t)=\left[\frac{1}{M}\sum_{j=1}^{M}\boldsymbol{X}_{j1}(t)\ \ \frac{1}{M}\sum_{j=1}^{M}\boldsymbol{X}_{j2}(t)\ \ \ldots\ \ \frac{1}{M}\sum_{j=1}^{M}\boldsymbol{X}_{jN}(t)\right] \tag{15}$$

where Y_{best} is the average best position of M particles based on the dimension of the variable. Hence, the updated equation becomes:

$$u_{jn}(t+1)=x_{jn}\pm\Omega\left|Y_{best}-u_{jn}(t)\right|\ln\left(\frac{1}{r}\right) \tag{16}$$

By using quantum behavior, the x_{jn} can be computed as:

$$x_{jn}=\theta x_{jn}+(1-\theta)x_{gn} \tag{17}$$

where θ is the random number in the range of $[0,1]$ of dimension N. The entire quantum behaved PSO process can be written in a single equation as:

$$U_j(t+1)=x_j\pm\Omega\left|Y_{best}-U_j(t)\right|\ln\left(\frac{1}{r}\right) \tag{18}$$

Figure 1 depicts the flowchart of the proposed algorithm incorporating QPSO for harmonic estimation, and the detailed procedure is given as follows.

1) Initialize QPSO parameters: the number of population size M, the number of dimensions N, T, W_2 = 1, W_1 = 1.

2) Initialize the population depending on M and N, and initialize the particle best history $\boldsymbol{X}_{jn}=[x_{j1}, x_{j2}, ..., x_{jN}]$ and global best history $\boldsymbol{X}_{gn}=[x_{g1}, x_{g2}, ..., x_{gN}]$.

3) Calculate the average best position value of M particles for N dimensions using (15).

4) Calculate the contraction expansion factor for each iteration t.

$$\Omega=(W_2-W_1)\frac{T-t}{T}+W_1 \tag{19}$$

5) Update particles using QPSO algorithm according to (16) and (17).

6) Compute the fitness value FIT by minimizing RSS value as:

$$FIT=\min(RSS) \tag{20}$$

7) Update the history of the particle x_{jn} if the current fitness value is less than the previous value.

8) Update the global history of the particle x_{gn} depending on the previous global value recorded.

9) Estimate the desired signal and other performance comparison parameters such as performance index (PER) and mean square error (MSE).

Estimate the amplitudes and phases of the harmonics using (9) and (10).

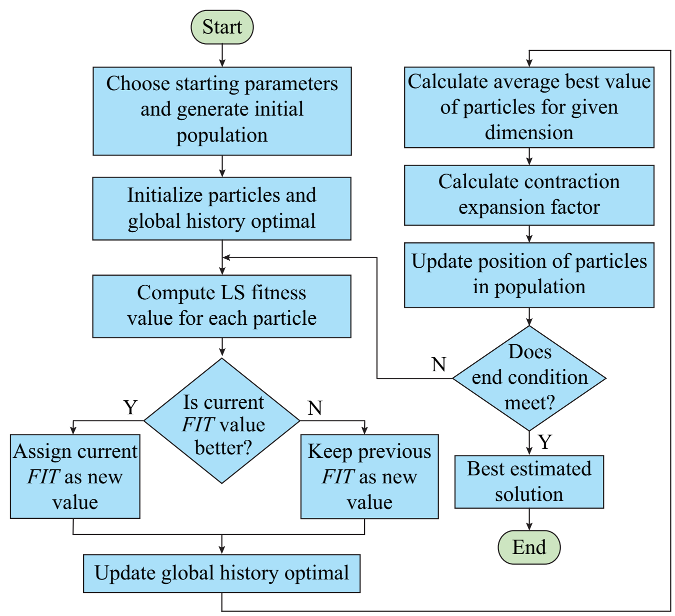

Fig. 1. Flowchart of proposed QPSO-LS to estimate harmonics.

IV. Simulation Results and Discussion

The harmonic estimation of different test signals has been carried out in this section to validate the performance of the proposed QPSO-LS algorithm. Most of the test signals are taken from the literature for comparative assessment. The algorithm has been applied to estimate the integer-harmonics in the presence of DC decaying offset. The strength of the proposed QPSO-LS has been authenticated by extracting the sub- and inter-harmonics in the power system signal in the presence of uniform and Gaussian noises. The application of the algorithm is extended to real-time examples of axial flux permanent magnet synchronous generator (AFPMSG) and LED lamp.

The difference between the power signal and the estimated signal yields the *RSS* as:

$$RSS = \sum (S - \hat{S})^2 \tag{21}$$

The essential objective function of the problem is to minimize the RSS in a highly non-linear and dynamic search domain [23] using (20). Most of the literature appraises the strength of the estimation techniques based on PER and MSE parameters used for comparative analysis of different methods [24]. The mathematical models of these parameters are given by:

$$MSE = \frac{\sum (S - \hat{S})^2}{n} \tag{22}$$

$$PER = \frac{\sum (S - \hat{S})^2}{\sum S^2} \tag{23}$$

The performance of the proposed approach has been evaluated based on the given statistical parameters.

The simulations for each case study are performed on Laptop: DELL Inspiron, Intel core i7 CPU 4610 @ 3.00 GHz processor, 4 GB RAM, and 64-bit operation system (Windows 7). The proposed QPSO-LS is programmed in MATLAB, and simulations are run on MATLAB R2018a®. The different parameters of QPSO-LS are set according to the nature of the case study and its vibrant behavior.

A. Integer-harmonic Estimation of Variable Frequency Drives

The generated signal consists of a DC decaying offset of $0.5\exp(-5t)$ in the presence of additive random noise at 10 dB (signalto noise) SNR. The harmonic contents of the actual signal are given in Table I.

TABLE I
TEST SIGNAL DEPLOYED FOR INTEGER-HARMONIC ESTIMATION

Harmonic order	Frequency (Hz)	Amplitude (p.u.)	Phase (°)
1	50	1.50	80
3	150	0.50	60
5	250	0.20	45
7	350	0.15	36
11	550	0.10	30

The continuous time signal has been sampled and discretized according to the Nyquist criterion considering 64 samples per cycle. The sampling frequency of the signal is considered to be 3.2 kHz.

The simulation for near-optimal extraction of harmonics has been executed on given signals. The proposed QPSO-LS is applied with 200 populations and a maximum of 600 iterations. Figure 2 shows actual and superimposed estimated signals along with their corresponding convergence characteristics. It is evident that QPSO-LS has converged within the first 200 iterations and becomes smooth for the next 400 iterations.

The proposed QPSO-LS is equated with previous techniques presented in the literature for comparative assessment listed in Table II, where BBO stands for biogeography based optimization.

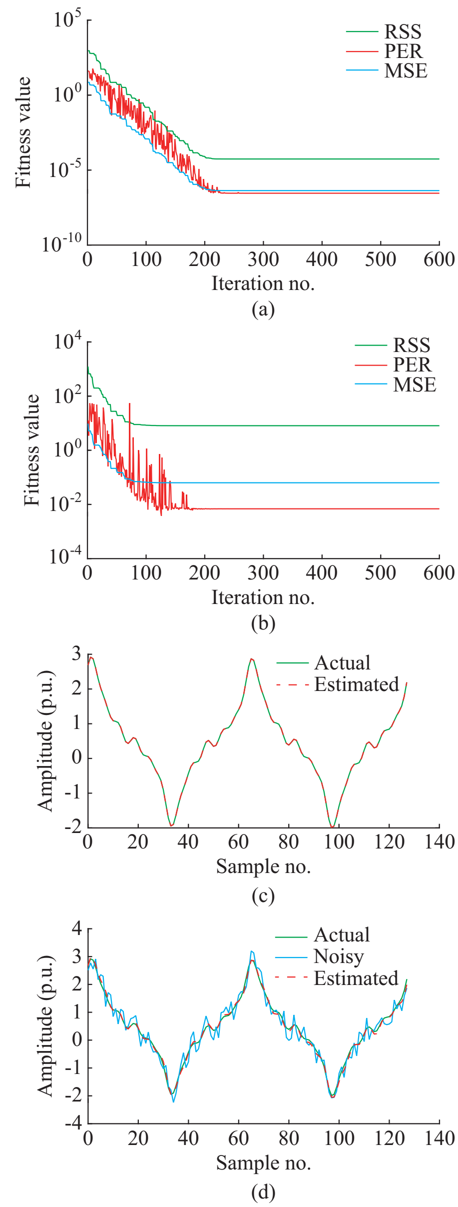

Fig. 2. Convergence characteristics and estimated signals for variable frequency drive. (a) Fitness value without noise. (b) Fitness value at 10 dB SNR. (c) Estimated signal without noise. (d) Estimated signal at 10 dB SNR.

The results reveal the robustness of proposed QPSO-LS for harmonic estimation in terms of estimating the amplitudes, phases, percentage errors, and computation time. From the numerical results, it is evident that the proposed QPSO-LS algorithm is superior to other techniques for harmonic estimation. Moreover, the proposed algorithm presents the promising results.

B. Sub- and Inter-harmonic Estimation

The signal of integer-harmonic estimation is further dishonored with sub- and inter-harmonics in the presence of additive random noise. The problem of considering sub- and inter-harmonic estimations yields a complex and non-linear search space. First, the signal is despoiled with a sub-harmonic of $0.505\angle 75°$ (20 Hz), inter-harmonics of $0.25\angle 65°$ (180 Hz) and $0.35\angle 20°$ (230 Hz).

TABLE II
RELATIVE PERFORMANCE FOR INTEGER-HARMONIC ESTIMATION

Algorithm	Parameter	Fundamental	3rd	5th	7th	11th	Computation time (s)
Actual	Frequency (Hz)	50.0000	150.00000	250.00000	350.00000	550.00000	
	Amplitude (V)	1.5000	0.50000	0.20000	0.15000	0.10000	
	Phase (°)	80.0000	60.00000	45.00000	36.00000	30.00000	
BFO	Amplitude (V)	1.4878	0.51080	0.19450	0.15560	0.10340	10.931
	Error (%)	0.8147	2.16310	2.72670	3.73890	3.42020	
	Phase (°)	80.4732	57.90050	45.82350	34.56060	29.12700	
BFO-RLS	Amplitude (V)	1.4942	0.49860	0.20180	0.15260	0.09860	9.345
	Error (%)	0.3840	0.28570	0.90210	1.76090	1.74600	
	Phase (°)	80.3468	58.54610	45.69770	34.80790	29.93610	
BBO-RLS	Amplitude (V)	1.4953	0.50040	0.20080	0.14900	0.09990	5.852
	Error (%)	0.3104	0.08501	0.42031	0.19605	0.08302	
	Phase (°)	79.7888	59.54100	45.51530	36.11650	30.01240	
QPSO-LS	Amplitude (V)	1.5002	0.50000	0.20000	0.15000	0.10000	1.226
	Error (%)	0.0150	0.00440	0.00330	0.00190	0.00100	
	Phase (°)	80.0017	60.00150	45.00190	36.00150	30.00100	

The resulting signal is estimated in the noise-free as well as in the noisy environment of 10 dB SNR. The performance evaluation, with actual and superimposed estimated signals, is demonstrated by Fig. 3. It is apparent that performance parameters continue to decrease drastically up to the order of 10^{-28} until the maximal number of iterations is reached. The test signal used for integer-harmonic estimation is the characteristic signal generated by variable frequency drives (VFDs), electric arc furnaces, and power electronic-based equipment in the industry [12]. An imitated signal used in [11] has been generated for harmonic extraction.

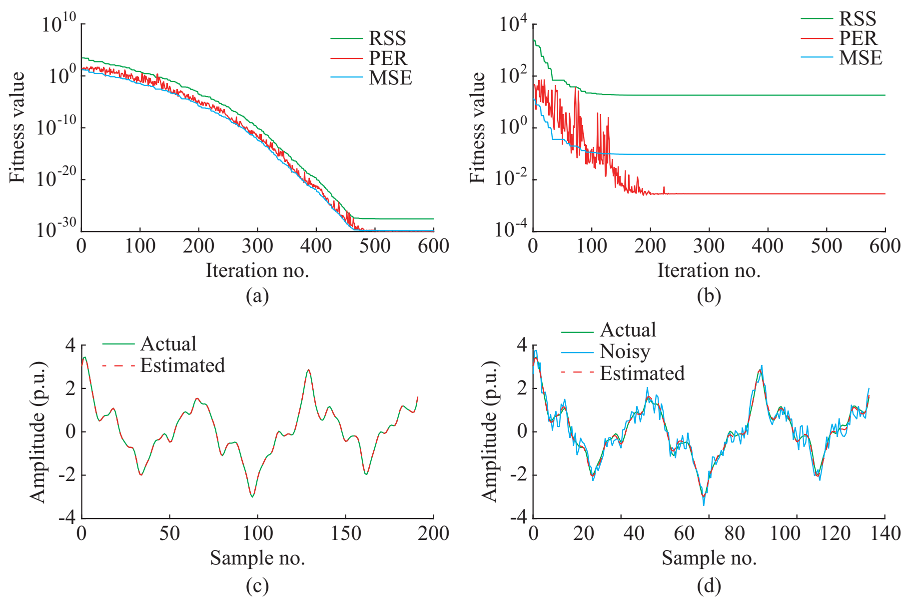

Fig. 3. Inter- and sub- harmonic convergence characteristics along with estimated signals. (a) Fitness value without noise. (b) Error value at 10 dB SNR. (c) Superimposed estimated signal without noise. (d) Estimated signal at 10 dB SNR.

The proposed QPSO-LS algorithm is compared with the existing techniques in literature for estimating the harmonics presented in the signals. The comparative assessment has been listed in Table III, which discloses the robustness of the proposed QPSO-LS algorithm. In Table III, ABC stands for artificial bee colony. The sturdiness of QPSO-LS algorithm becomes evident under noisy conditions. The evaluation gives far good results as compared to other techniques presented in the literature in terms of PER even at 10 dB SNR. Numerical results presented in Table IV signify the proposed QPSO-LS algorithm under extensive noisy conditions.

C. Real-time Voltage Estimation of AFPMG

Renewable energy technologies are becoming more popular in recent decades because of ever-increasing energy demand, prices of fossil-based fuels, and the pollution of conventional energy-producing sources [25].

TABLE III
RELATIVE PERFORMANCE UNVEILED BY DIFFERENT TECHNIQUES FOR SUB- AND INTER-HARMONICS

Algorithm	Parameter	Sub-harmonic	Fundamental	3^{rd}	Inter-harmonic 1	Inter-harmonic 2	5^{th}	7^{th}	11^{th}	Computation time (s)
Actual	Frequency (Hz)	20.00000	50.00000	150.0000	180.00000	230.00000	250.0000	350.00000	550.00000	
	Amplitude (V)	0.50500	1.50000	0.5000	0.25000	0.35000	0.2000	0.15000	0.10000	
	Phase (°)	75.00000	80.00000	60.0000	65.00000	20.00000	45.0000	36.00000	30.00000	
BFO-RLS	Amplitude (V)	0.51100	1.50290	0.4921	0.25810	0.36390	0.2009	0.14790	0.10150	12.837
	Error (%)	1.19000	0.19520	1.5887	3.23720	3.96510	0.4541	1.41490	1.48000	
	Phase (°)	74.81000	79.91480	59.0760	65.34450	19.86770	46.2780	36.44730	30.06430	
ABC-LS	Amplitude (V)	0.50600	1.49692	0.4912	0.24106	0.33701	0.4988	0.14707	0.09845	8.9543
	Error (%)	1.22500	0.20520	1.7532	3.57450	3.71250	0.5526	1.95570	1.55450	
	Phase (°)	74.85300	80.07330	59.4211	64.76300	19.96500	45.2916	35.79930	29.97730	
FA-RLS	Amplitude (V)	0.49900	1.49840	0.5004	0.24570	0.34970	0.2009	0.14970	0.09990	6.7543
	Error (%)	1.18811	0.10667	0.0800	1.72000	0.08571	0.4500	0.20000	0.10000	
	Phase (°)	74.93100	79.94800	59.5410	65.20300	19.97300	45.5230	36.12800	30.01260	
BBO-RLS	Amplitude (V)	0.49430	1.49840	0.5003	0.24580	0.34970	0.2008	0.14850	0.09990	6.7525
	Error (%)	1.12550	0.10455	0.0785	1.65055	0.07875	0.4452	0.95570	0.10000	
	Phase (°)	74.93210	79.95000	59.5228	65.17060	19.97750	45.5200	36.11790	30.01230	
QPSO-LS	Amplitude (V)	0.50500	1.50000	0.5000	0.25000	0.35000	0.2000	0.15000	0.10000	1.2362
	Error (%)	8.7×10^{-14}	0	1.1×10^{-13}	8.8×10^{-14}	3.1×10^{-14}	1.1×10^{-13}	3.7×10^{-14}	2.0×10^{-13}	
	Phase (°)	75.00000	80.00000	60.0000	65.00000	20.00000	45.0000	36.00000	30.00000	

TABLE IV
COMPARISON OF PER PARAMETER COMPUTED BY APPLICATION OF DIFFERENT ALGORITHMS

Algorithm	PER at different SNRs				
	No noise	40 dB	20 dB	10 dB	0 dB
BFO	11.78×10^{-2}	0.1380000	0.807300	5.25490	
BFO-RLS	8.70×10^{-2}	0.0920000	0.787000	4.54820	
ABC-RLS	7.52×10^{-2}	0.0895000	0.655400	4.25450	
FA-RLS	7.52×10^{-2}	0.0785000	0.561000	3.97450	
BBO-RLS	6.58×10^{-2}	0.0750000	0.573500	3.85550	
QPSO-LS	1.27×10^{-28}	0.0003203	0.019015	0.30752	2.1892

Among numerous electrical energy production sources, the wind is less costly [26].

AFPMGs are replacing radial flux permanent magnet generators (RFPMGs) in modern wind turbine technologies because of the unique features unveiled by AFPMG such as higher torque-to-weight ratio, maximum power density, high efficiency, absence of cogging torque losses, compact structure, lightweight and low operation shaft speed [27]-[29]. A 3-phase, multi-stage AFPMSG [30] is designed, whose per unit voltage waveform is taken as a power signal for harmonic estimation. An oscilloscope is used to record the voltage waveform of AFPMSG at a sampling frequency of 10 kHz. The output voltage for single phase is shown in Fig. 4(a).

The robust QPSO-LS algorithm is applied for harmonic estimation of the voltage signal for the first 15 integer-harmonics. The problem of the estimation is executed by taking 200 particles and running the algorithm for 600 iterations. Figure 4(b) gives the estimation performance over the iterations. It is evident that the problem converges below 300 iterations. The amplitudes of the first 15 integer-harmonics are also highlighted. The computation time for this case study is 2.161 s.

D. Real-time Harmonic Analysis of Current Drawn by LED Lamp

Recently, LED lamps are replacing incandescent bulbs and fluorescent lights because of the energy-saving capability. The LED lamps operate on 12 V DC voltage and are connected with power electronic-based circuitry to behave as a non-linear device in the modern power system. The LED lights draw non-linear current from the primary source and thus distort the voltage waveform of the whole system by inoculating the harmonics. For this case study, a digital oscilloscope is used to record and save the output of the current value with 250 samples per cycle. The algorithm is applied for 8 odd harmonics with 200 iterations and 200 particles.

As the actual signal is degraded due to the noise at positive and negative peaks, it was observed that the performance of the algorithm is not up to the mark and needs some signal processing techniques to remove this noise. For this purpose, a concept of decimation followed by the interpolation is employed, which gives the best results, as shown in Fig. 5(a). The actual signal is down-sampled by a factor of 5 and 7, respectively. The proposed QPSO-LS algorithm takes 0.7753 s, and the PER computation value is 0.33595 for this case study.

Moving average filter (MAF) may also be employed for smoothing the actual signal before harmonic estimation.

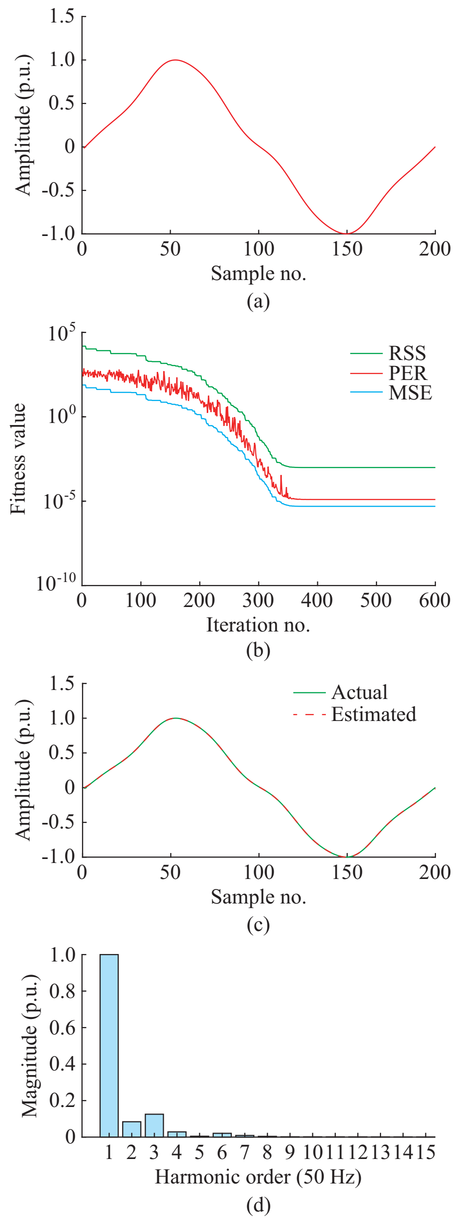

Fig. 4. Voltage estimation and harmonic analysis of AFPMSG. (a) Measured single-phase voltage waveform of AFPMG model. (b) Fitness characteristics. (c) Superimposed estimated signal. (d) Integer-harmonic magnitude.

For this case study, the span of MAF is varied from 10-25 points and harmonic estimation is carried out for the minimum value of RSS at the 17-point MAF. The abrupt changes become smooth as gleaned from the graph, after passing through MAF. And the estimation shows promising results. The total time taken by the simulation using MAF is 0.7938 s.

E. Full-wave Six-pulse Bridge Rectifier

The voltage signal from a full-wave six-pulse bridge rectifier has been considered for the extraction of harmonics in the presence of additive noise [16]. A petite version of the power system is shown in Fig. 6, which consists of two buses: a generation bus and a load bus. The contents of the power signal are listed in Table V.

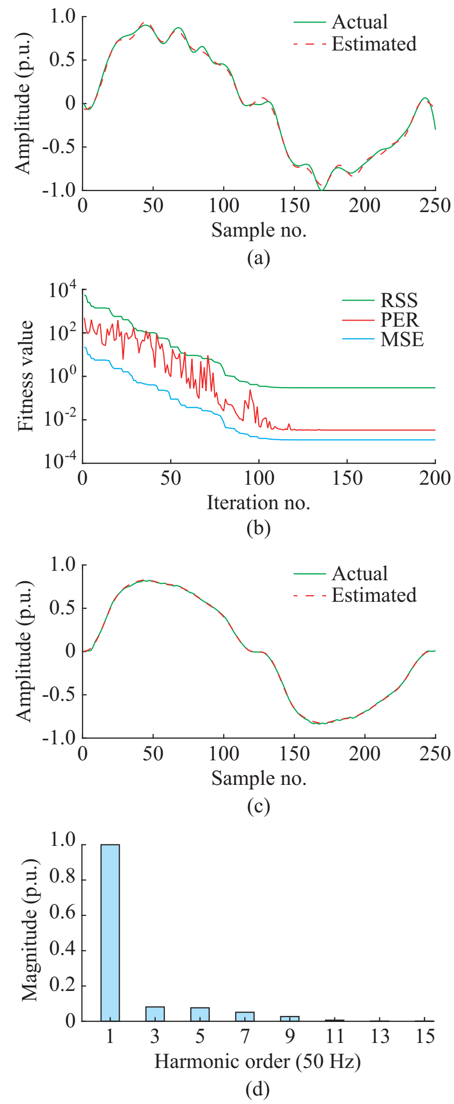

Fig. 5. Estimation and harmonic analysis of current drawn by LED lamp. (a) Estimation with decimation. (b) Fitness characteristics. (c) Estimation with MAF. (d) Integer-harmonic amplitude using MAF.

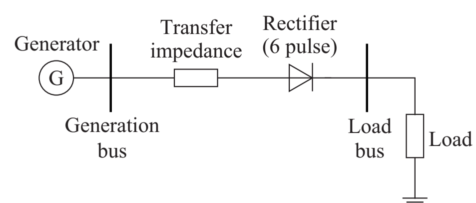

Fig. 6. Two-bus small power system.

TABLE V
HARMONIC CONTENTS OF TEST SIGNAL

Harmonic order	Frequency (Hz)	Amplitude (p.u.)	Phase (°)
1	50	0.950	–2.02
5	250	0.090	82.10
7	350	0.043	7.90
11	550	0.030	–147.10
13	650	0.033	162.60

The noisy power signal consisting of the above-mentioned harmonic contents is generated considering 64 samples per cycle at 50 Hz.

The algorithm minimizes the evaluation parameters tremendously up to the order of 10^{-30}, as shown in Table VI, where the average time using GA, PSOPC, and QPSO-LS are 4.3492, 3.4846, and 1.2263, respectively. The percentage error that occurs after estimation in amplitudes and phases is less than 10^{-13} and approaches to zero. The evaluation has also been performed in the presence of uniform and Gaussian noises at different SNR levels, and the results are compiled for comparative assessment. The tabulated results confirm the strength and superiority of the proposed QPSO-LS in terms of less PER and computation time.

TABLE VI
RELATIVE PERFORMANCE OF SIX-PULSE BRIDGE RECTIFIER

Scenario	SNR (dB)	PER		
		GA	PSOPC	QPSO-LS
Uniform noise	No noise	0.0570	1.28×10^{-17}	5.8490×10^{-30}
	20	0.1706	4.50×10^{-3}	1.4955×10^{-2}
	10	0.2068	2.63×10^{-2}	7.6996×10^{-2}
	0	0.5206	4.55×10^{-1}	4.6104×10^{-2}
Gaussian noise	No noise	0.0570	1.2800×10^{-17}	7.5140×10^{-30}
	20	0.3995	5.0400×10^{-2}	1.2280×10^{-1}
	10	2.3962	1.1319	2.2939×10^{-1}
	0	2.8913	2.6316	2.7166

F. Statistical Analysis of Proposed QPSO-LS Approach

Harmonic estimation is the problem of accurately computing the amplitudes, phases, and additive random noise in the electrical voltage or current signals using the meta-heuristic approach. Statistical parameters are required to benchmark the estimated signals, and also to measure the goodness of the estimation. For this purpose, two well-known statistical parameters have been selected as given in (20) and (22), respectively [23]. The PER given in (23) has also been commonly used for harmonic estimation problems in [4], [11], [19]. Based on these three parameters, simulations are performed to compare the results with recent approaches, as discussed earlier for each case study.

To prove the validity of the proposed QPSO-LS optimization method, another statistical analysis can also be characterized by giving the boxplot after several simulation runs [9]. The boxplot is a standardized way of displaying the entire span of values (distribution of data) based on 6 numbers as follows: minimum, first quartile, second quartile (median), third quartile, maximum, and outliers [23]. The boxplot of the QPSO-LS algorithm has been acknowledged for 100 simulation runs, as shown in Fig. 7, for sub- and inter-harmonic estimation.

From the boxplot, it is apparent that the optimal solution is located between the minimum and maximum values with the least number of outliers. Thus, the analysis justifies that the proposed QPSO-LS algorithm can estimate the actual signal optimally in the minimum computation time and with the highest accuracy compared to other approaches.

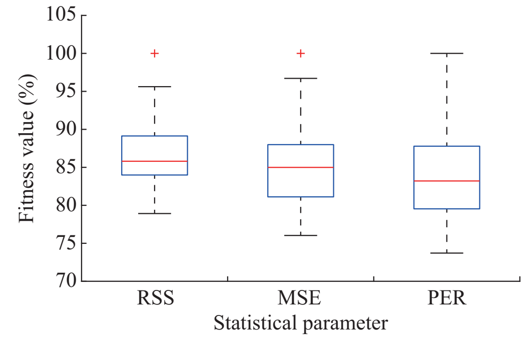

Fig. 7. Boxplot to validate proposed QPSO-LS for sub- and inter-harmonic estimation.

For the detailed analysis, the statistical parameters such as the best cost, worst, mean, and standard deviation are shown in Table VII for each case study considering RSS as the objective function.

TABLE VII
STATISTICAL ANALYSIS OF PROPOSED QPSO-LS

Case study	Best	Worst	Mean	Standard deviation
1	5.50×10^{-5}	5.50×10^{-5}	5.50×10^{-5}	2.03×10^{-18}
2	2.72×10^{-28}	3.68×10^{-28}	3.12×10^{-28}	1.80×10^{-29}
3	9.87×10^{-4}	9.87×10^{-4}	9.87×10^{-4}	3.12×10^{-18}
4	1.39×10^{-2}	1.39×10^{-2}	1.39×10^{-2}	1.77×10^{-17}
5	1.69×10^{-30}	3.53×10^{-30}	2.13×10^{-30}	3.07×10^{-31}

V. CONCLUSION

A QPSO-LS method has been proposed for valid estimation of both phases and amplitudes from noisy power signals. Simulation results demonstrate that the proposed scheme is capable of estimating the effects of substantial distortions by analyzing the accuracy, robustness, and convergence characteristics. Different theoretical and real-time case studies have been explored to evaluate the performance of the approach. Integer-, inter-, and sub-harmonics are extracted from power signals at different uniform and Gaussian noise levels. We have concluded that the proposed QPSO-LS provides accuracy performance superior to the conventional classical approaches with less computation time. Moreover, our simulation study on the robustness against different imperfection has demonstrated that quantum optimization could outperform the conventional methods. This diversity of QPSO-LS exhibits the versatility of algorithms in solving nonlinear and complex optimization problems.

REFERENCES

[1] S. K. Jain, P. Jain, and S. N. Singh, "A fast harmonic phasor measurement method for smart grid applications," *IEEE Transactions on Smart Grid*, vol. 8, no. 1, pp. 493-502, Jul. 2016.

[2] J. M. Guerrero, "Guest editorial special issue on power quality in smart grids," *IEEE Transactions on Smart Grid*, vol. 8, no. 1, pp. 379-381, Jan. 2017.

[3] T. Lobos, T. Kozina, and H. Koglin, "Power system harmonics estimation using linear least squares method and SVD," in *Proceedings of the 16th IEEE Instrumentation and Measurement Technology Conference*, Venice, Italy, May 1999, pp. 789-794.

[4] S. K. Singh, N. Sinha, A. K. Goswami *et al*., "Several variants of Kalman filter algorithm for power system harmonic estimation," *International Journal of Electric Power*, no. 78, pp. 793-800, Jan. 2016.

[5] E. A. A. Al-Feilat, I. El-Amin, and M. Bettayeb, "Power system harmonic estimation: a comparative study," *Electric Power System Research*, vol. 29, no. 2, pp. 91-97, Mar. 1994.

[6] M. Bettayeb and U. Qidwai, "Recursive estimation of power system harmonics," *Electric Power System Research*, vol. 47, no. 2, pp. 143-152, Mar. 1998.

[7] M. Mohammadi, F. Talebpour, E. Safaee *et al*., "Small-scale building load forecast based on hybrid forecast engine," *Neural Process Letter*, vol. 48, no. 1, pp. 329-351, Oct. 2017.

[8] A. Abid, T. N. Malik, and M. M. Ashraf, "Combined emission economic dispatch of power system in presence of solar and wind using flower pollination algorithm," *Mehran University Research Journal of Engineering & Technology*, vol. 38, no. 3, pp. 581-598, Jul. 2019.

[9] M. M. Ashraf and T. N. Malik, "Least cost generation expansion planning in the presence of renewable energy sources using correction matrix method with indicators-based discrete water cycle algorithm," *Journal of Renewable Sustainable Energy*, vol. 11, no. 5, p. 056301, Oct. 2019.

[10] O. Abedinia, M. Bekravi, and N. Ghadimi, "Intelligent controller based wide-area control in power system," *International Journal of Uncertainty Fuzzy*, vol. 25, no. 1, pp. 1-30, Feb. 2017.

[11] S. K. Singh, N. Sinha, A. K. Goswami *et al*., "Robust estimation of power system harmonics using a hybrid firefly based recursive least square algorithm," *International Journal of Electric Power Energy Systems*, vol. 80, pp. 287-296, Sept. 2016.

[12] P. K. Ray and B. Subudhi, "BFO optimized RLS algorithm for power system harmonics estimation," *Applied Soft Computation*, vol. 12, no. 8, pp. 1965-1977, Mar. 2102.

[13] S. Biswas, A. Chatterjee, and S. K. Goswami, "An artificial bee colony-least square algorithm for solving harmonics estimation problems," *Applied Soft Computation*, vol. 13, no. 5, pp. 2343-2355, Jan. 2013.

[14] M. Bettayeb and U. Qidwai, "A hybrid least squares-GA-based algorithm for harmonic estimation," *IEEE Transactions on Power Delivery*, vol. 18, no. 2, pp. 377-382, May 2003.

[15] S. Mishra, "A hybrid least square-fuzzy bacterial foraging strategy for harmonic estimation," *IEEE Transactions on Evolution Computing*, vol. 9, no. 1, pp. 61-73, Feb. 2005.

[16] Z. Lu, T. Ji, W. Tang *et al*., "Optimal harmonic estimation using a particle swarm optimizer," *IEEE Transactions on Power Delivery*, vol. 23, no. 2, pp. 1166-1174, Apr. 2008.

[17] B. Subudhi and P. Ray, "A hybrid adaline and bacterial foraging approach to power system harmonics estimation," in *Proceedings of 2010 International Conference on Industrial Electronics, Control & Robotics (IECR)*, Orissa, India, Dec. 2010, pp. 236-242.

[18] T. Ji, M. Li, Q. Wu *et al*., "Optimal estimation of harmonics in a dynamic environment using an adaptive bacterial swarming algorithm," *IET Generation, Transmission & Distribution*, vol. 5, no. 6, pp. 609-620, Aug. 2011.

[19] S. K. Singh, N. Sinha, A. K. Goswami *et al*., "Optimal estimation of power system harmonics using a hybrid firefly algorithm-based least square method," *Soft Computing*, vol. 21, no. 7, pp. 1721-1734, Sept. 2015.

[20] D. Yumin and Z. Li, "Quantum behaved particle swarm optimization algorithm based on artificial fish swarm," *Mathematical Problems in Engineering*, pp. 1-10, Aug. 2014.

[21] F. P. Mahdi, P. Vasant, M. M. Rahman *et al*., "Quantum particle swarm optimization for multiobjective combined economic emission dispatch problem using cubic criterion function," in *Proceedings of IEEE International Conference on Imaging, Vision and Pattern Recognition (icIVPR)*, Dhaka, Bangladesh, Apr. 2017, pp. 1-5.

[22] J. Sun, W. Fang, V. Palade *et al*., "Quantum-behaved particle swarm optimization with Gaussian distributed local attractor point," *Applied Mathematics and Computation*, vol. 218, no. 7, pp. 3763-3775, Dec. 2011.

[23] J. A. Rice, "Summarizing data," in *Mathematical Statistics and Data Analysis*, Belmont, USA: Thomson Higher Education, 2006, pp. 377-408.

[24] S. K. Singh, N. Sinha, A. K. Goswami *et al*., "Power system harmonic estimation using biogeography hybridized recursive least square algorithm," *International Journal of Electric Power*, vol. 83, pp. 219-228, Apr. 2016.

[25] M. M. Ashraf, T. N. Malik, and M. Iqbal, "Peak load sharing based on blade pitch control of wind turbine in the presence of utility supply," *Journal of Renewable and Sustainable Energy*, vol. 6, no. 1, pp. 13-110, Jan. 2014.

[26] M. M. Ashraf, T. N. Malik, S. Zafar *et al*., "Design and fabrication of radial flux permanent magnet generator for wind turbine applications," *Nucleus*, vol. 50, no. 2, pp. 173-181, Jun. 2013.

[27] M. M. Ashraf and T. N. Malik, "A modified model of axial flux permanent magnet generator for wind turbine applications," *Nucleus*, vol. 51, no. 3, pp. 391-395, Dec. 2014.

[28] M. M. Ashraf, T. N. Malik, and M. Iqbal, "Development of a prototype micro wind energy system with adjustable blade pitch for experimentation purposes at laboratory level," *Nucleus*, vol. 51, no. 1, pp. 75-86, Dec. 2014.

[29] J. F. Gieras, R. Wang, and M. J. Kamper, "Introduction," in *Axial Flux Permanent Magnet Brushless Machines*, 2nd ed., Dordrecht, Netherlands: Springer Science & Business Media, 2008, pp. 1-19.

[30] M. M. Ashraf and T. N. Malik, "Design of three-phase multi-stage axial flux permanent magnet generator for wind turbine applications," *Turkish Journal of Electrical Engineering and Computer Science*, vol. 25, no. 1, pp. 520-538, Feb. 2017.

Abu Bakar Waqas received his B.Sc. and M.Sc. degrees in electrical engineering from the University of Engineering and Technology Taxila, Taxila, Pakistan, in 2011 and 2013, respectively. He served his Alma Mater as a Lecturer for four years and is now a Ph. D. Scholar at Fudan University, Shanghai, China. His research interests include quantum computation, quantum communications, smart grid, and optimization of electrical engineering problems.

Muhammad Mansoor Ashraf received his B.Sc. and M.Sc. degrees in electrical engineering from the University of Engineering and Technology Taxila, Taxila, Pakistan, in 2011 and 2013, respectively. Currently, he is serving as Lecturer at the University of Engineering and Technology Taxila and pursuing his Ph. D. degree there. His research interests include power system transmission and distribution planning, power system optimization and integration of renewable energy resources into grid.

Yasir Saifullah received his B.Sc. and M.Sc. degrees in electrical engineering from University of Engineering and Technology Taxila, Taxila, Pakistan. He is currently pursuing his Ph.D. degree with the Department of Communication Science and Engineering, Fudan University, Shanghai, China. His research interests include quantum computation, microwave, antenna design and metamaterials.