LCL Filter Design of STATCOM using Genetic Algorithm Scheme for SCIG Based Microgrid Operation

Nitin Kumar Saxena [1#] Anmol Gupta,[1] Mohd Faisal Jalil [2] Varun Gupta [1] and R. C. Bansal [3,4]

[1]Department of Electrical & Electronics Engineering, KIET Group of Institutions, Ghaziabad, India
[2]Department of Electrical Engineering, Aligarh Muslim University, Aligarh, India
[3]Department of Electrical Engineering, University of Sharjah, Sharjah, United Arab Emirates
[4]Department of Electric, Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa

CONTENTS

Abstract—In a microgrid static Compensator (STATCOM) is the most prominent inverter circuit for stabilizing the bidirectional power flow requirements of the system. This inverter circuit is the primary source of harmonics when the supply current feeds from the microgrid to the main grid. Improved control strategy and proper filter design may give solution to these issues and so, there is a huge scope of research in the field of the converter control techniques and filter designing for such microgrid based power system. The key objectives of this paper are (i) to develop an adequate current control scheme for adjusting real and reactive power fluctuations produced by load time to time, and (ii) to reduce the harmonic level of output characteristics in terms of real and reactive power flow and current frequency. For this, an approach is presented to estimate the filter design parameters for current controlled STATCOM connected to squirrel cage induction generator (SCIG) based microgrid. A nature-inspired optimization namely, genetic algorithm (GA), is implemented to estimate the most suitable parameters for the LCL filter. Results obtained through GA are validated with a conventional mathematical method in terms of real and reactive power flow through microgrid along with harmonic-based studies.

Keywords: microgrid, LCL filter, sTATCOM, GA optimization, power system management

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Address correspondence to Mohd Faisal Jalil, Department of Electrical Engineering, Aligarh Muslim University, Aligarh, India. E-mail: mohdfaisaljalil@zhcet.ac.in

[#]Electrical and Computer Engineering Department, University of Denver, Denver, USA.

1. INTRODUCTION

Microgrid integration has evolved significantly over the last few decades, transitioning from diesel genset-based systems to renewable energy sources such as solar photovoltaic, wind, and biogas. This paradigm shift arises from the changing landscape of social and environmental challenges, which demand cleaner and more sustainable power generation solutions. The focus has thus shifted to creating efficient, resilient, and environmentally friendly microgrid configurations. As a result, the need for innovative operational and control mechanisms, along with seamless integration into the main grid, has prompted substantial research in this area.

The establishment of smart grids has played a pivotal role in enabling the integration of microgrids into the larger power network [1–3]. These intelligent systems facilitate bidirectional communication between various components of the grid, allowing for enhanced monitoring, control, and optimization. Furthermore, the design and optimization of hybrid microgrids have garnered attention due to their potential to address technical, environmental, and economic considerations [4–9]. Key factors such as system stability, energy efficiency, and cost-effectiveness are carefully weighed in the development of such microgrids.

Operating and control challenges, especially in islanded microgrid scenarios, have been subject to thorough investigation [10–12]. The ability to ensure stable and reliable operation while disconnected from the main grid requires sophisticated control strategies. In this context, the utilization of Squirrel Cage Induction Generator (SCIG) based microgrids has gained prominence. These microgrids provide robust and low-maintenance operation but demanding solutions for reactive power management at the local level for voltage stability issues. Reactive power, being a localized phenomenon, is optimally managed within the microgrid, while surplus real power can be seamlessly transferred to the national grid [13–16].

To address the complexities of power flow dynamics and demand fluctuations within microgrids, the design and implementation of inverter circuits assume vital significance. The Static Compensator (STATCOM) emerges as a proven shunt-connected power electronic circuit that effectively handles voltage control and reactive power balance. The integration of DC storage further enhances the capability of real power management. The constituents of the STATCOM circuit encompass the converter circuit, firing angle control, DC link, gate pulse generator, and filter circuit. Firing angle control and DC linkage have been extensively discussed in existing literature [10], while pulse-width modulation (PWM) based gate pulse generation is elucidated in [17].

The filter circuit plays a pivotal role in mitigating harmonics and optimizing power balance in the microgrid system. Different filter designs, ranging from L filter to LC and LCL filters, have been explored in the context of inverter circuits. The LCL filter has emerged as a popular choice due to its superior performance. Tuning LCL parameters is crucial for optimal performance, and the synthesis of experience-based and analytical approaches can enhance the design process. Advanced machine learning algorithms have demonstrated their potential in achieving this synergy by combining mathematical models, training data, and constraints to create robust and efficient filter designs [18]. Nature-inspired optimization techniques, such as genetic algorithms, provide a pathway to incorporate experiential and analytical insights into filter design [19–21].

In this paper, a Genetic Algorithm (GA) based LCL filter design, augmented with damping resistance, is proposed. The study aims to validate the effectiveness of the GA algorithm in comparison to conventional mathematical tools. The evaluation encompasses the enhancement of real and reactive power balance, demonstrating the practical application of the proposed GA-based technique in a microgrid scenario.

In conclusion, the evolution of microgrid integration from conventional diesel gensets to renewable-based sources necessitates innovative operational and control mechanisms. The focus on enhancing power balance, voltage stability, and harmonic mitigation has led to the development of advanced solutions like current controlled SCIG-based microgrids and optimized LCL filters. The proposed Genetic Algorithm-based approach offers a promising avenue for improving microgrid performance and advancing the state of the art in this dynamic field.

2. SYSTEM CONFIGURATION

As in Figure 1, a SCIG based microgrid is presented with STATCOM as inverter circuit and load connected with main grid [22]. The purpose of this STATCOM would be, as stated above, to provide instant reactive power balance and to mitigate the THD level with GA designed LCL filter. A 4 pole, 50 Hz, 4 kW squirrel cage asynchronous machine which is available in MATLAB Simulink model is used for this work and is operated at −4% slip to get its operation as induction generator. Load real power demand will be primarily given by SCIG. Full detail for configuring this machine, which is available in MATLAB Simulink library, as SCIG based microgrid has been presented in [23]. Grid will entertain the flow of real power in either direction depending on the load changes. Reactive power requirement of load as well as SCIG will be attained with STATCOM only to keep the reactive power as local area phenomenon.

2.1. STATCOM Configuration

It has already been elaborated how the role of STATCOM is very critical to maintain the reactive power flow in system as local area phenomenon. And hence, the key

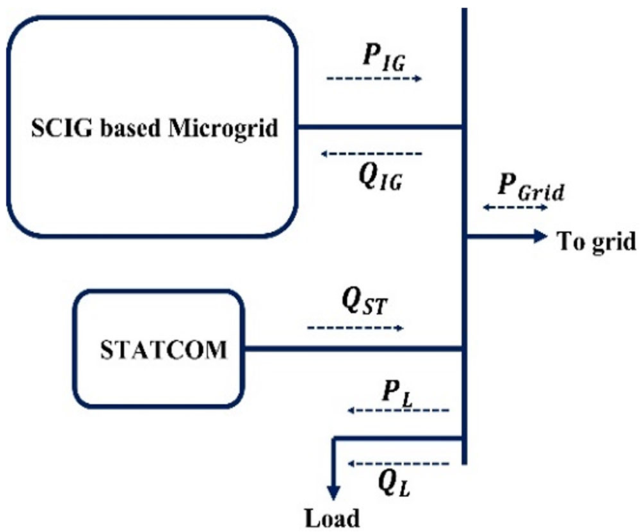

FIGURE 1. Layout for SCIG based microgrid with STATCOM.

emphasis of this paper is to implement an adequate current control arrangement for adjusting real and reactive power fluctuations produced by load time to time and to reduce the harmonic level of output characteristics in terms of real and reactive power flow and current frequency. Clubbing these two requirements as two important current control and filter design blocks, Figure 2 explains the basic configuration of STATCOM.

The reactive power expression is presented in Equation (1) [24] for the STATCOM's power flow modeling.

$$Q_{ST} = (kV_{dc})^2 B_{ST} - kV_{dc} V_L B_{ST} \cos\alpha \tag{1}$$

STATCOM regulates reactive power generation or absorption in the system by altering the firing angles of the thyristor for adequate control of the inverter current with respect to the bus voltage. Pulse generator block generates the signal according to these feedbacks from output terminal of STATCOM.

The reactive power of STATCOM, as provided in Equation (1), is explained in [25] as being a function of two major variables: supply voltage and firing angle. The function of the DC link voltage is the supply voltage. In order to modify the firing angle in the event of a dynamic disturbance and to supply the necessary reactive power, the DC link voltage must first be established.

$$\cos\alpha = \frac{(kV_{dc})^2 B_{ST} - Q_{ST}}{kV_{dc} V_L B_{ST}} \tag{2}$$

In this current control scheme-based block, firing angle adjusts by the setting of gain constants K_P and K_I of PI controller which adjusts through the reference signal of controller. The gain constants evaluation requires an objective function and a criterion to achieve it. Frequency deviation is considered as objective function and integral of Square Error (ISE) criterion is used as performance criterion [26]. Mathematically, the integral square error criterion is defined as

$$\eta_{ISE} = \int_0^\infty f^2(t)dt \tag{3}$$

As the Simulink block gives the signal in discrete data so ISE criterion must be applied in discrete form [27],

$$\eta_{ISE} = \sum_{n=1}^{k} F_n^2 \times n \tag{4}$$

The values of K_P and K_I are chosen using conventional iterative procedure in which value of ISE is optimized with the support of MATLAB codes followed by the concepts of Ziegler Nichols method as shown in Figure 3.

The selection of K_P and K_I values are suggested using soft tuning methods in several research articles. However, this paper limits the value estimation using conventional method only so that the main emphasis can be given to the effect of filer parameters on the system performance. This filter is necessary to mitigate the THD and waveform distortion in output performance [28]. As in Figure 4, LCL filter is proposed due to its proven superiority over L and LC filter [29]. LCL filters offer improved decoupling between the filter and the grid impedance, lower current ripple across the grid inductor, and can aid in lessening the impact of switching frequency. Grid-connected inverters increase their capacity for reactive electricity and put a strain on the system with their filter circuits [30]. In the current work, LCL filter is designed and integrated with proposed STATCOM configuration. However, the detail discussion about its proposed scheme is presented in subsequent section.

3. MATHEMATICAL MODELING FOR LCL FILTER

The basic LCL filter model per phase is shown in Figure 4. The choice of inductor is an important component in designing the L-C-L filter. Choosing the capacitor C_f is also a crucial component of designing. L_1 is the inductor on the STATCOM side, while L_2 is the inductor on the grid side. The choice of inductor and capacitor is made so that lower order harmonics should travel through an inductor while higher order harmonics should pass through

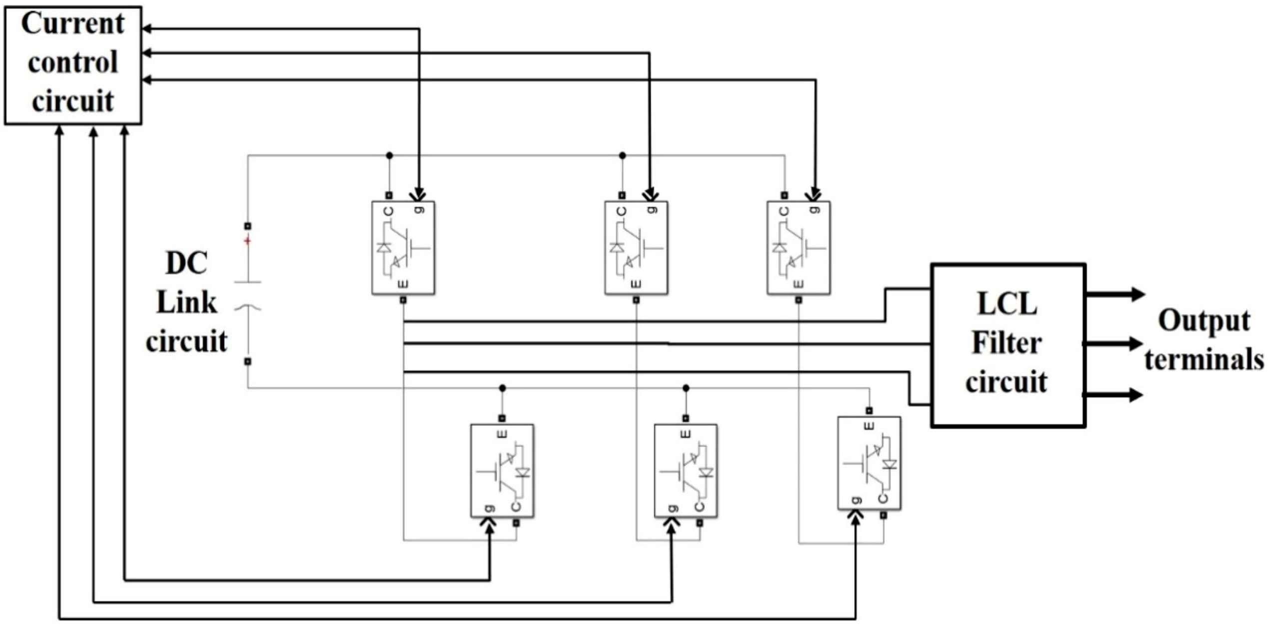

FIGURE 2. Layout of STSTACOM current control scheme.

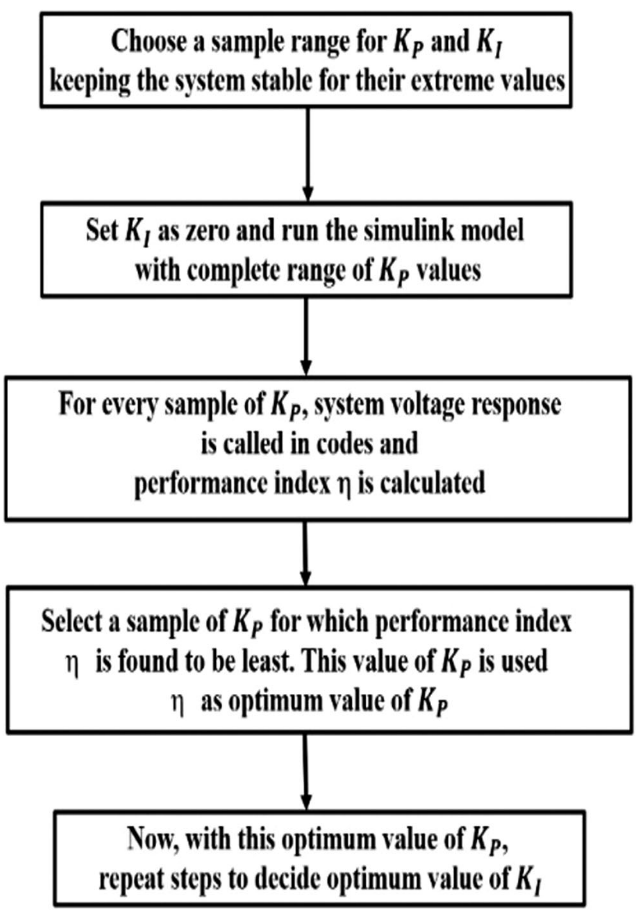

FIGURE 3. Flowchart of conventional tuning method.

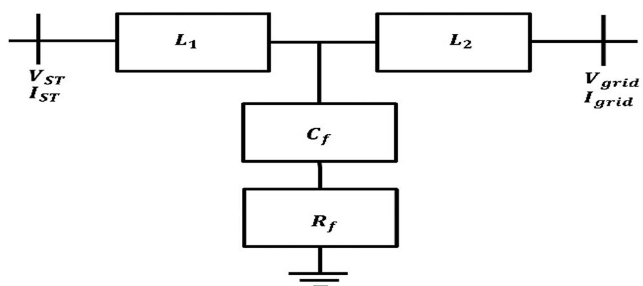

FIGURE 4. Layout of LCL filter between STATCOM and grid.

the capacitor [31,32]. Before proceeding to the proposed algorithm, reference values of all filter parameters must be known. Transfer function is a tool that can help in analyzing the stability and their outcomes this proposed estimation of LCL filter design. The damping resistance R_f and other formulas including their symbolic notations, together with the transfer function of the LCL filter, are as follows in [33,34].

$$G(s) = \frac{1 + C_f R_f s}{L_1 C_f L_2 s^3 + C_f (L_1 + L_2) R_f s^2 + (L_1 + L_2) s} \tag{5}$$

$$L_1 = \frac{V_{dc}}{6 f_s \Delta I_{L,\max}} \tag{6}$$

$$Z_b = \frac{V_L^2}{Q} \tag{7}$$

$$C_b = \frac{1}{\omega_{grid} Z_b} \tag{8}$$

$$C_f = 10\% C_b \tag{9}$$

$$k_a = 0.2$$

$$L_2 = \frac{\sqrt{\frac{1}{k_a^2} + 1}}{C_f \omega_s^2} \tag{10}$$

$$\omega_{res} = \sqrt{\frac{L_1 + L_2}{L_1 L_2 C_f}} \tag{11}$$

$$R_f = \frac{1}{3\omega_{res} C_f} \tag{12}$$

4. PARAMETER ESTIMATION USING GA

The mathematical formulae for estimating the reference parameters of LCL Filter is expressed in section 3. These mathematical expressions give the analytical values of parameters however, there is a still scope of improving these values using experience-based training with machine learning. Improved parameters values result into minimizing the harmonics effects, total harmonic distortions (THD) and waveform distortions errors. These errors reflect in current frequency, performance of reactive and real power at load terminal.

As conventional mathematical methods are not able to find the feasible solution with non-linearity, time-delays, and uncertainty present in the system dynamics [35–37]. Therefore, to obtain the satisfactory performance of the system there is a need to estimate the parameters of LCL filter with automatic tuning methods like GA based tuning method. Genetic algorithm is very simple and fast optimization algorithm method, available in literature [38]. The GA algorithm is used to find the optimum solution of the problem under test by measuring the fitness value with many generations and iteration will end when it finds the best solution according to the fitness function. Therefore, GA based automatic tuning technique is used to estimate the constraints of the LCL filter. The main steps of the algorithm are given below:

1. Initialize the population
2. Generation iterations are selected based on population size of the problem under test.

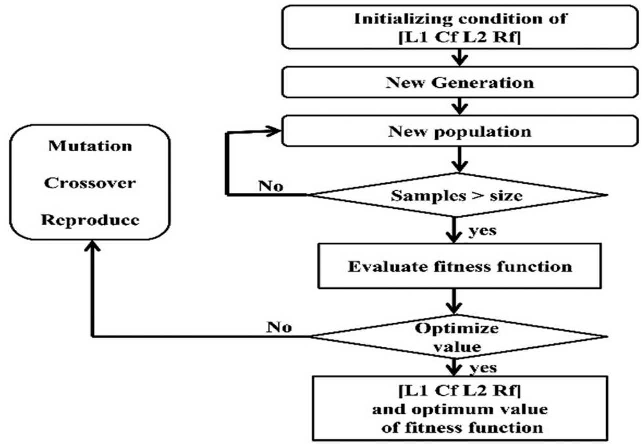

FIGURE 5. Flow chart for STATCOM tuning using GA.

   i. The execution of the program in each population by assigning the fitness value according to the fitness measure.
   ii. There are 3 phases i.e., Reproduction, crossover and mutation in genetic algorithm which are used to develop new population sets.
      a. Reproduction: In this phase fitness function evaluation and operator selection is performed.
      b. Crossover: In this phase local search for the optimum solution is performed. The operator from Crossover/reproduction develops two offspring for each of the parent under selection operator. The crossover process helps to develop new solutions set from the available solutions for the problem. After that, it selects the most suitable solution for the problem among all.
      c. Mutation: In this phase global search for the optimum solution is performed. In this process the best solution is selected from among all.
3. Iterations are repeated until the best solution to the problem close to an optimal solution is found to meet stopping criterion.

As the drawbacks of conventional method i.e., poor performance convergence and loss of best solution can be removed by using real coded genetic algorithm. Hence, the GA algorithm is applied in this work to find the optimum parameters of gain constants i.e., proportional (K_P) and integral Gain (K_I). The performance indices ISE is selected to estimate the parameter of the controller in STATCOM. The first conventional method is used to initialize the operator for GA algorithm and then GA algorithm is used to find the best solution by global search in the search space. The real-coded genetic algorithm is used in this work to get the ideal value for the filter parameters with the help of

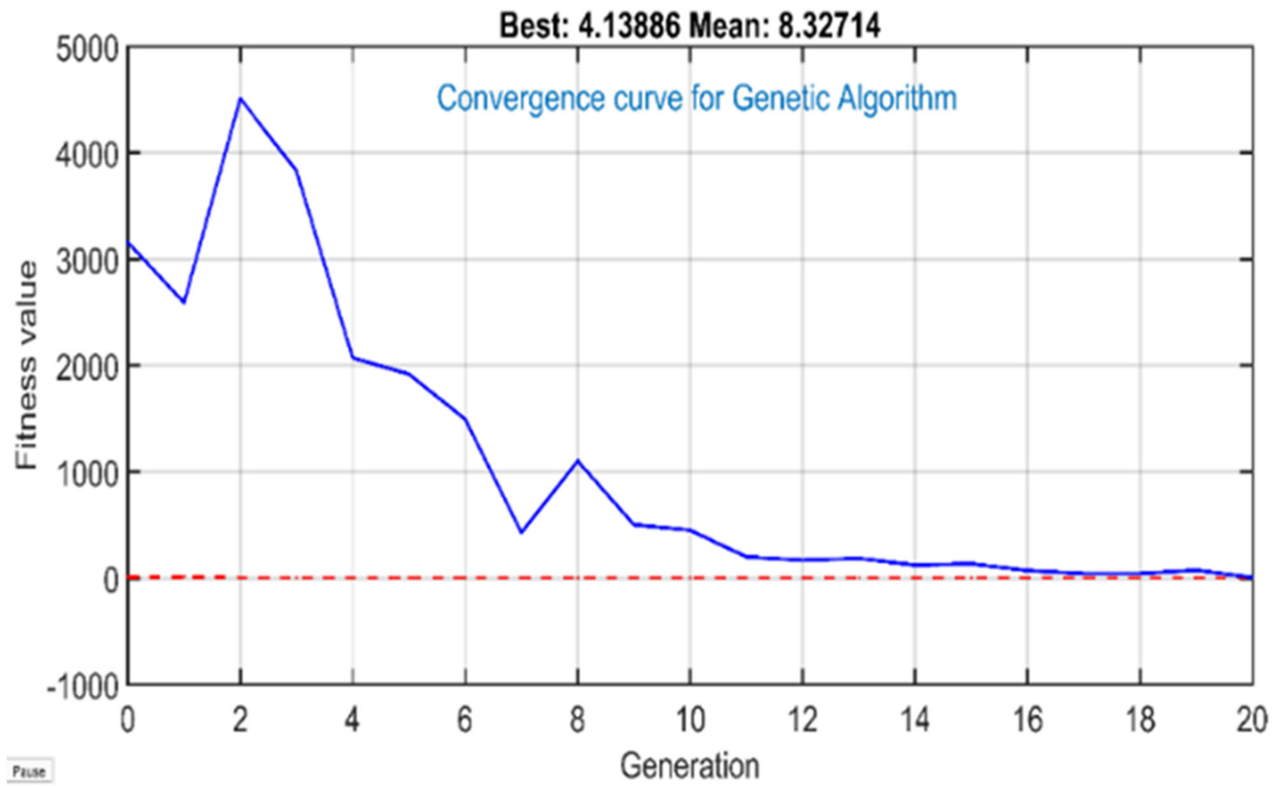

FIGURE 6. Comparison convergence curve for GA method.

Parameters	Conventional mathematical method	Genetic Algorithm based method
L_1	0.0566 H	0.1231 H
L_2	3.8197e–05 H	4.8819e–05 H
C_f	3.9789e–05 F	2.4110e–04 F
R_f	0.3265 Ω	0.1071 Ω

TABLE 1. Filter design and estimated parameters.

MATLAB software. Technically five comprehensive stages for applying GA technique, as illustrated in flow chart for execution of Genetic Algorithm, is given in Figure 5. Parameters obtained from conventional method are chosen as reference parameters and other parameters are chosen as in [26].

5. RESULTS AND DISCUSSION

It has been elaborated how SCIG based microgrid requires a dynamic reactive power compensator when connected with main grid. Also, during load changes and in starting active power and reactive power flow need much attention otherwise power quality at load as well as grid ends might not be acceptable. STATCOM with advanced filter design can reduce the effect of harmonic distortions and thus the same is presented in this paper. The various steps including filter designs for STATCOM have already been explained in previous sections. This section validates those explanations with real time system performance.

Basic layout of the proposed filter includes four parameters as shown in Figure 4. These parameters are estimated with the help of conventional method which exhibits through mathematical expressions as in Eqs. (6) to (12). Considering these values as reference value genetic algorithm is applied as in Figure 5 and parameters are recreated using this GA tuning. The acceptability of GA training can be visualized with the help of convergence curve as shown in Figure 6. Estimated parameters from both the methods; conventional and GA are compared in Table 1. System stability improves with GA over conventional method. For this, Figure 7 presents bode plot obtained with conventional method first and then superiority of genetic algorithm-based method is compared over it.

To understand the role and importance of STATCOM filter design with SCIG based microgrid, it is necessary to analyze the real and reactive power balance first for the system shown in Figure 1. As explained in earlier sections, renewable based microgrids are the new additions in

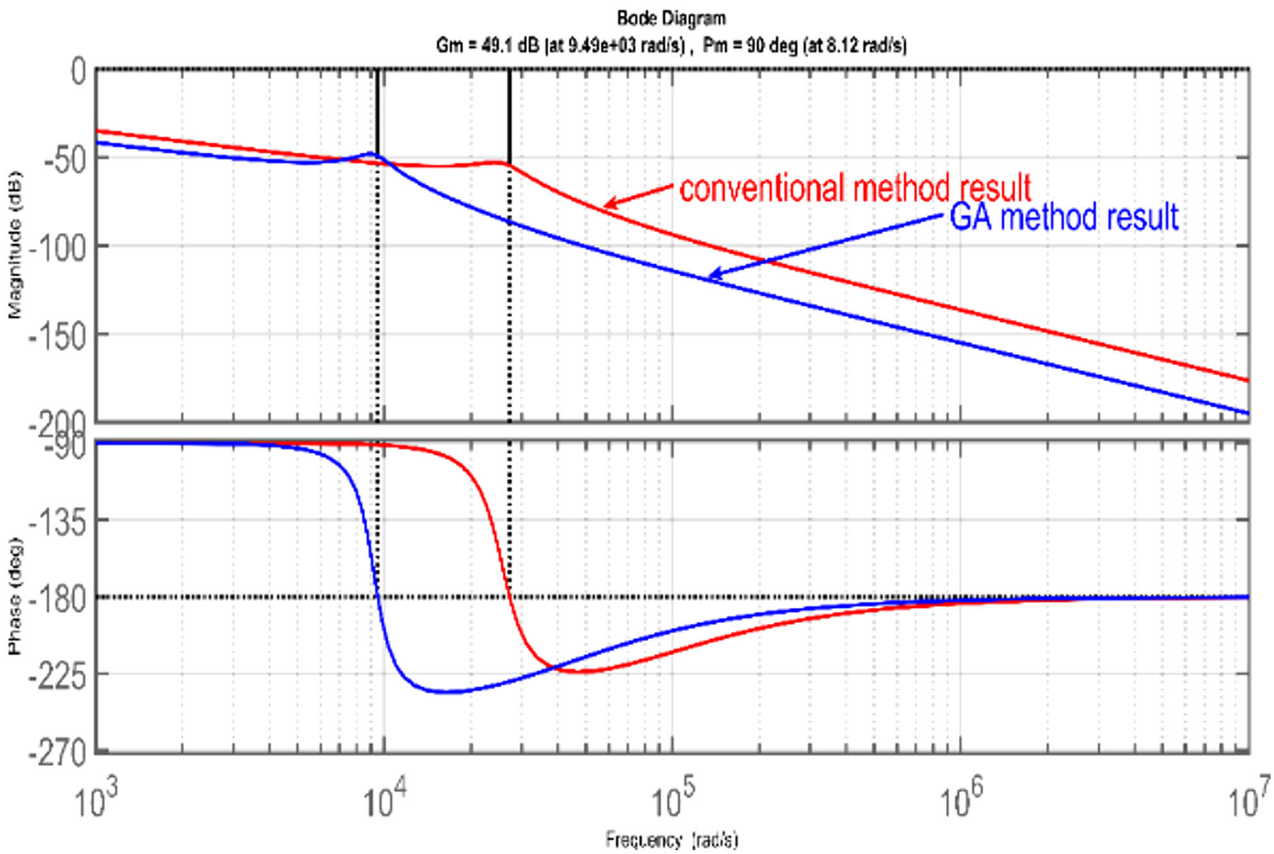

FIGURE 7. Comparison between conventional and GA method using Bode plot.

modern power system. Technically, it primarily focuses to maintain the bidirectional real power flow. It means that microgrid can supply real power to grid and can receive real power from grid as per necessity. However, reactive power must be balanced at microgrid end. This means grid should not be participated in supplying any additional reactive power demand of microgrid or load. The developed model validates the above said technical philosophy even with conventional method of filter selection. Figures 8 and 9 are the real power and reactive power balance for the proposed system with conventional STATCOM filter design method. It can be noticed that 0.2 per unit (PU) real power is generated by SCIG in Figure 8 and load requirement is only 0.1 PU. So, remaining real power is transferred to grid and STATCOM is at zero level. In Figure 9, load and SCIG both are demanding reactive power, which is supplied by STATCOM, and grid is at zero level. But it is also found that these power balancing in both the figures take time to settle down the system from starting condition due to STATCOM poor filter design. Therefore, advanced method is required to investigate the better filter design and so, GA is adopted in the proposed work.

The procedure for applying GA is explained with the help of flowchart as in Figure 5. With epochs etc. presented in Figure 6, the Figures 10 and 11 represent how the harmonics effect reduces with GA. In both the figures, blue color graphs represents GA performance over red color dashed graphs of conventional method. It can be visualized how starting transient conditions and settling conditions can be improved with GA over conventional method. Now, the system power balance performance can be examined with GA tuned filter design and same is illustrated in Figures 12 and 13. Results show the improved performance with GA method.

Figures 10 and 11 show a comparison about real and reactive power flow through both the methods and the power quality improvements using GA tuned LCL filter design method can be visualized there. However, more analysis can be done with the help of grid current and converter current in the system. And so, for validating proposed LCL filter design using GA conventional method is also examined with the reduction in THD level at grid current and converter current level as shown in Figure 14.

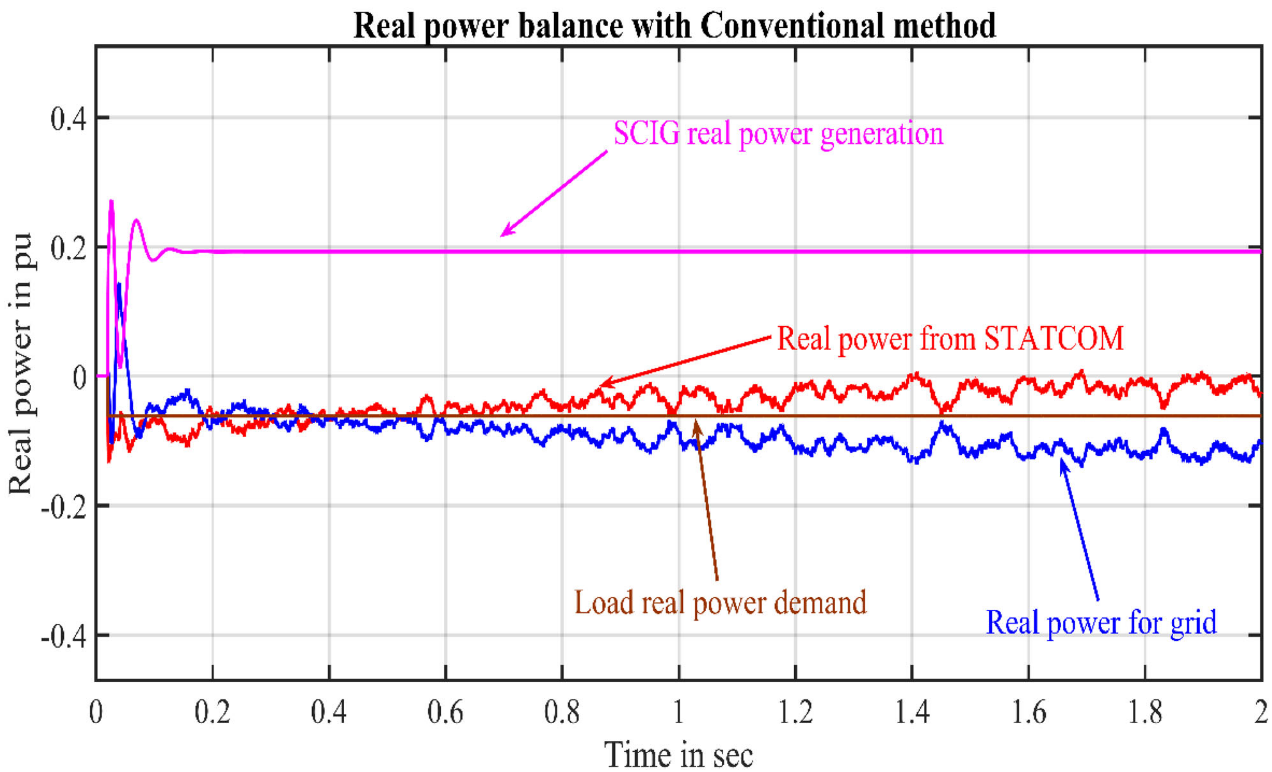

FIGURE 8. Real power balance with conventional method based STATCOM filter design.

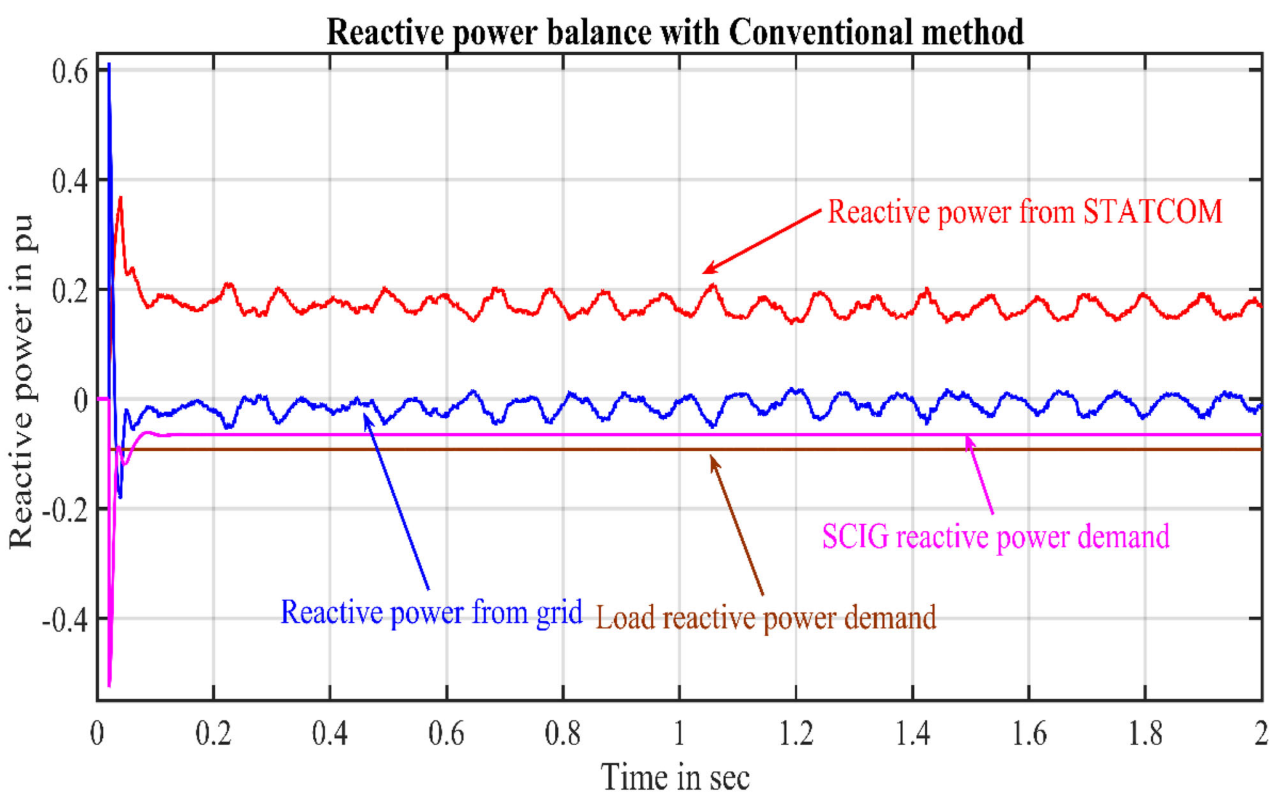

FIGURE 9. Reactive power balance with conventional method based STATCOM filter design.

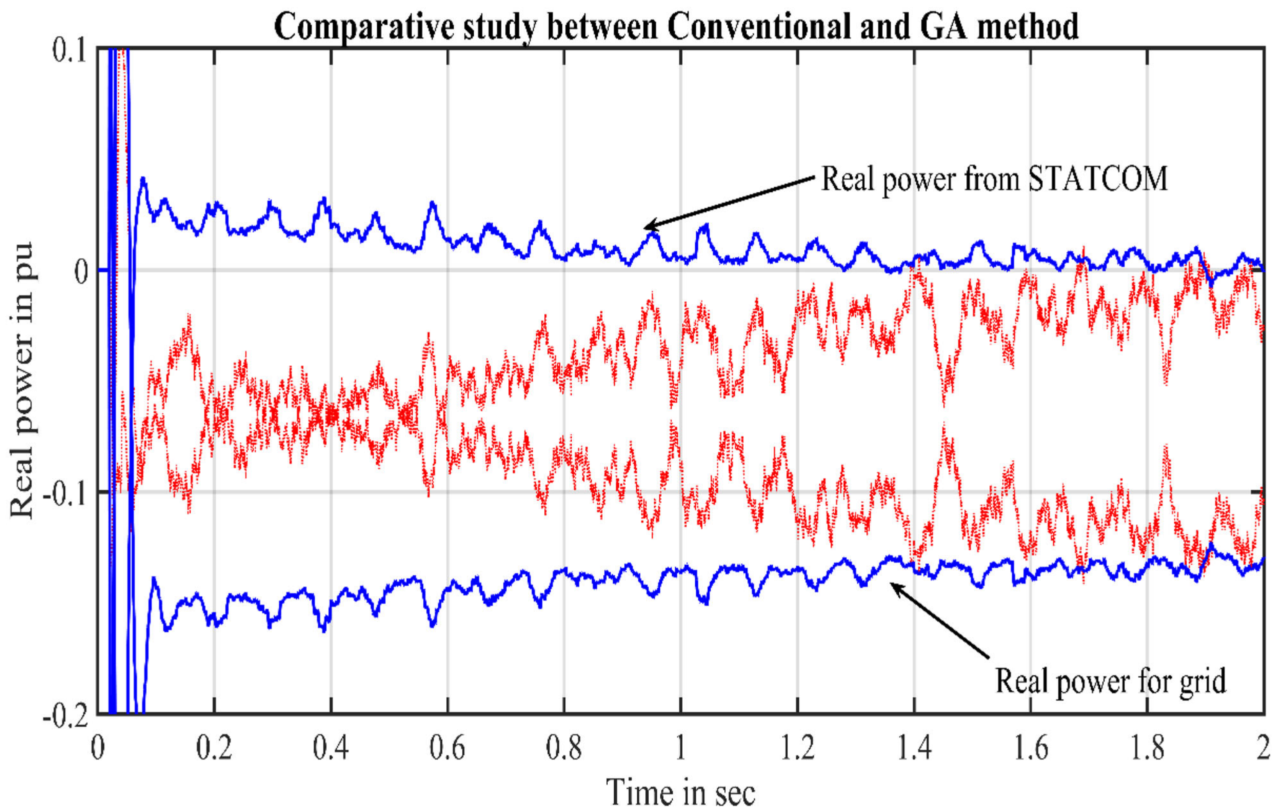

FIGURE 10. Real power comparison for conventional method and GA.

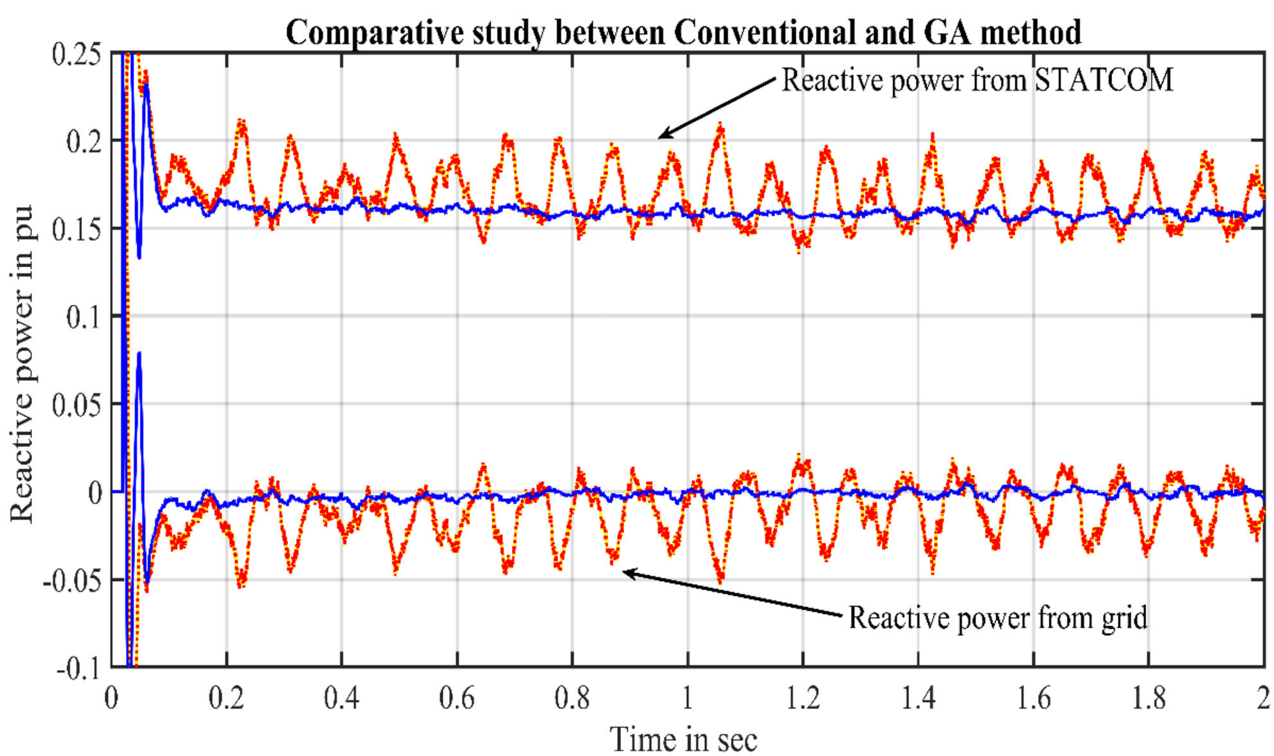

FIGURE 11. Reactive power comparison for conventional method and GA.

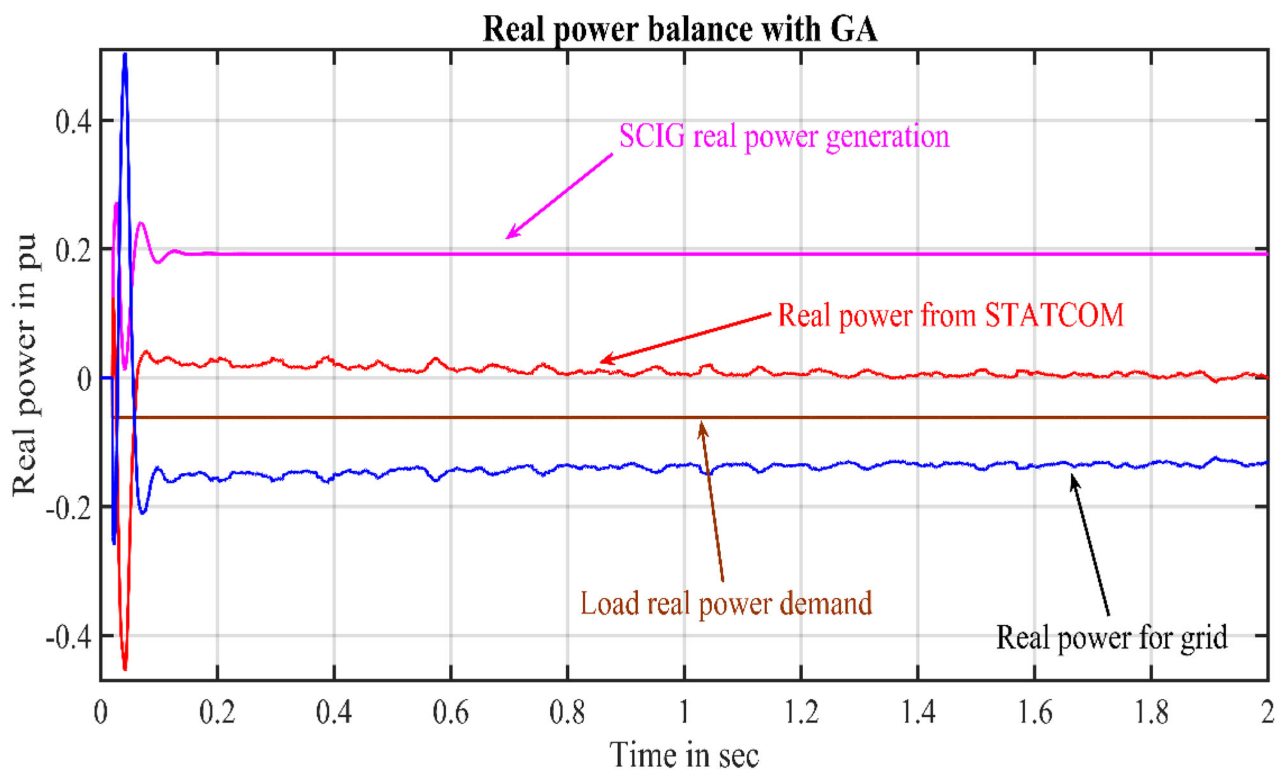

FIGURE 12. Real power balance with GA based STATCOM filter design.

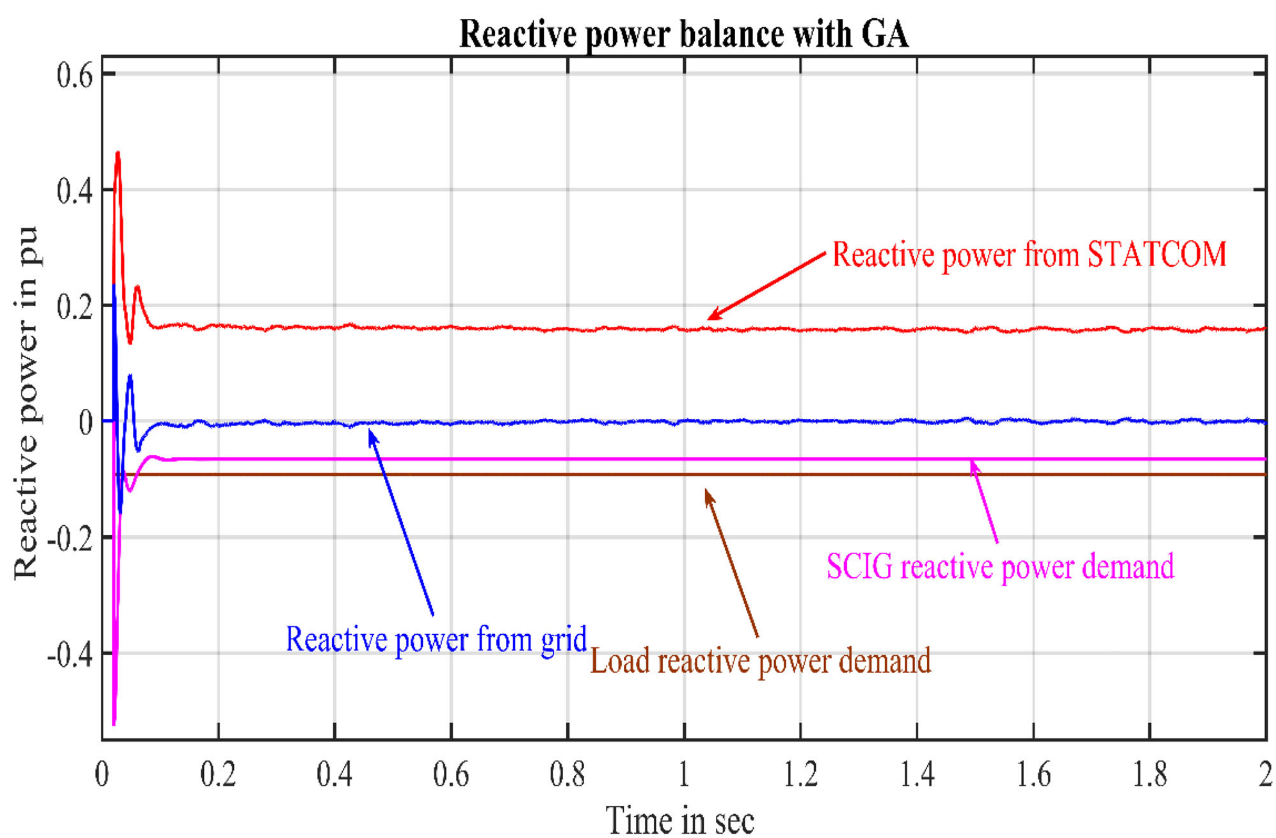

FIGURE 13. Reactive power balance with GA based STATCOM filter design.

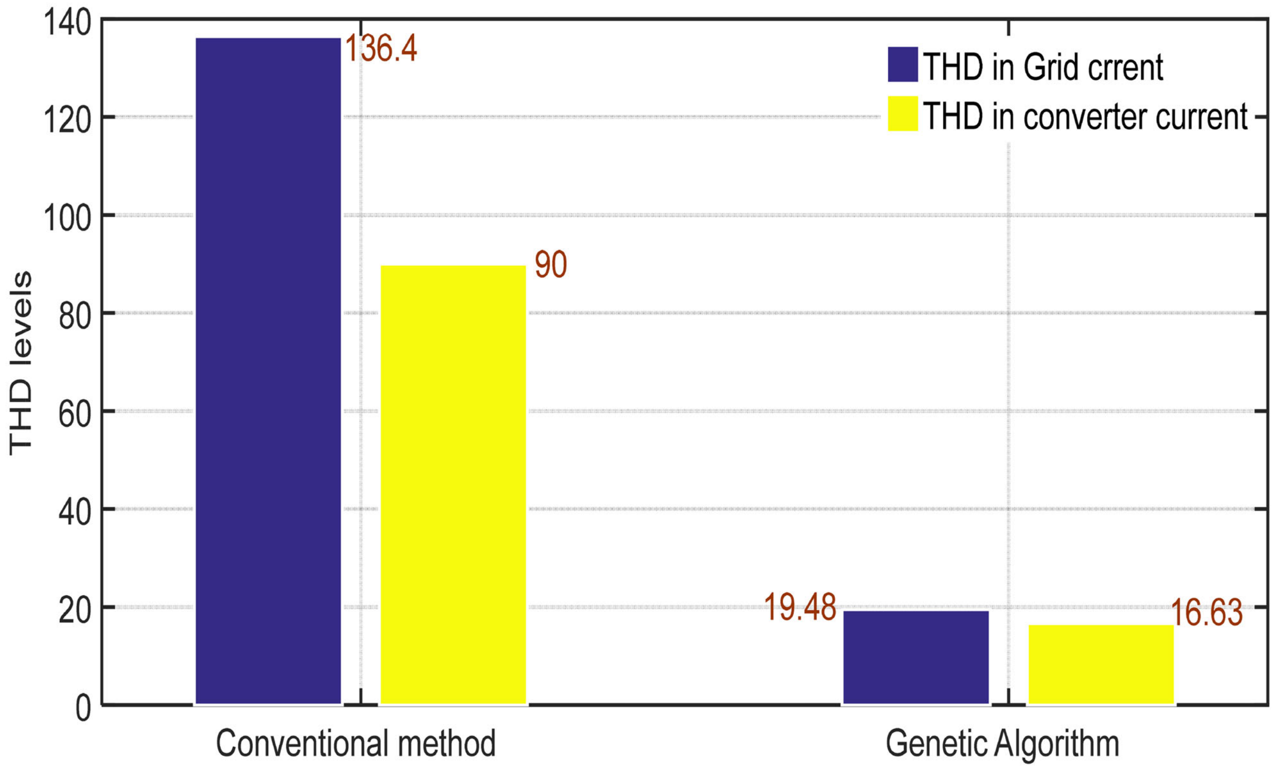

FIGURE 14. THD level comparison for grid and converter current using proposed approach.

6. CONCLUSION

In this paper, a SCIG based microgrid is connected to main grid. As load and SCIG require additional reactive power to operate such system and it must be balanced at local level. STATCOM is used for the same so that reactive power requirement can be fulfilled without the involvement of main grid. It has also been seen how surplus real power is supplied to grid but reactive power contribution from the grid is zero. STATCOM is a converter-based switching circuit and causes power quality issues when connected with system. STATCOM circuit control is important due to the requirement of bidirectional flow of powers. Apart from its control mechanism, filter design is also one of the most identified research areas to reduce the harmonic level and waveform distortions. So, a proper filter design is required to resolves such power quality issues in converter and grid currents. This paper explained nature inspired optimization technique namely Genetic Algorithm to estimate the value of LCL filter parameters. Conventional method which gives analytical method to find the parameters of L and C in LCL filter is used as reference method and genetic algorithm is applied to investigate the optimum value of filter parameters.

Convergence curve elaborated the acceptable GA tuning for the system. Bode plot for filter transfer function, real and reactive power balance in micro-grid based electrical system model are compared. The results shown in Figures 8–14 validate the acceptability of GA scheme for getting the optimum value of LCL filter parameters for STATCOM.

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ORCID

Nitin Kumar Saxena http://orcid.org/0000-0002-6520-1749
Mohd Faisal Jalil http://orcid.org/0000-0003-0781-4026
Varun Gupta http://orcid.org/0000-0002-0390-9266
R. C. Bansal http://orcid.org/0000-0002-1725-2648

DATA AVAILABILITY STATEMENT

The data sources employed for analysis are presented in the text.

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BIOGRAPHIES

Nitin Kumar Saxena, a senior IEEE member, having more than 20 years of experience in engineering teaching, research and administration, has received his Ph.D., M.Tech. and B.E. from National Institute of Technology Kurukshetra, Indian Institute of Technology Delhi and MJP Rohilkhand University Bareilly respectively. Presently, he is working as Visiting Faculty in University of Denver, USA. He is also associated as Professor (Research) with KIET Group of Institutions, Ghaziabad, India. Before this, he has worked as Associate Professor in Wolaita Sodo University, Ethiopia for 2 years and Head & Assistant Professor (Senior) in Moradabad Institute of Technology, Moradabad, India for 15 years. His broad area of interest includes deregulated power systems, FACTs devices, electric market, ancillary services, computer applications in power system and hybrid power systems.

Anmol Gupta is an Assistant Professor in the Department of Electrical & Electronics Engineering at KIET Group of institutions, Delhi-NCR, Ghaziabad. He is an academician and researcher of having more than 15 years of experience in engineering teaching, and administration. He has received his Ph.D. in the field of Renewable energy sources from National Institute of Technology, Kurukshetra and he has received his M.Tech. and B.Tech. from Rajasthan Technical University, Kota and Uttar Pradesh Technical University, Lucknow respectively. He has published 20+ SCI/SCIE/Scopus/UGC Journals, 18 International/National Conferences, and 2 Books Chapters and he has also guided 3 M.Tech. thesis.

Mohd Faisal Jalil has more than 10 years of teaching and research experience. He is a Senior Member of IEEE. Currently, he is working as an Assistant Professor in the Electrical Engineering department, Aligarh Muslim University, Aligarh, India. He has also served as Assistant Professor at KIET Group of Institutions, Delhi-NCR, Ghaziabad, India, during 2013–2021. He received his Ph.D. from the Electrical Engineering department, Jamia Millia Islamia (JMI), New Delhi, India. He obtained his B. Tech and M. Tech from the Electrical Engineering department, Aligarh Muslim University, Aligarh, India, in 2010 and 2012, respectively. He has published several research papers in reputed journals and conferences. His research interests include electrical machines, renewable energy systems, and PV systems under partial shading conditions.

Varun Gupta completed his B.Tech in Electronics and Communication Engineering from BIT, Meerut in 2007, M.Tech from Dr. B.R. Ambedkar National Institute of Technology (NIT) Jalandhar in 2011 and Ph.D. from National Institute of Technology (NIT) Kurukshetra in 2020. He is serving as an Associate Professor in Electronics and Instrumentation Engineering Department, KIET Group of Institutions, Ghaziabad, India for the last nine years. He has published number of research papers in several reputed international and national journals and along with conferences. He is active reviewer of several journals including IETE Technical Review, IET Signal Processing, IRBM, Analog Integrated Circuits and Signal Processing, Wireless Personal Communications, International Journal of Medical Engineering and Informatics, International Journal of Control and Electrical Engineering, etc. His research includes biomedical signal processing, control system, pattern recognition techniques, soft computing, Edge Computing, LSTM networks, malware detection in medical IoT devices and image processing.

R. C. Bansal has over 25 years of teaching, research, academic leadership, and industrial experience. Currently he is Professor in EE Dept. at University of Sharjah, UAE and Extraordinary Professor at University of Pretoria, South Africa. In previous postings, he was Professor and Group head (Power) at University of Pretoria, and worked with University of Queensland, Australia; USP, Fiji; BITS Pilani, India. Prof. Bansal has published over 400 journal articles, conf. papers, books/ book chapters. He has Google citations of over 18000 and h-index of 65. He has supervised 25 PhD and 5 Post Docs. Prof. Bansal has significant attracted significant funding from Industry and Government Organisations. He is an Editor of reputed journals including IEEE Systems Journal, IET-RPG, TESGSE. He is a Fellow, and CP Engg IET-UK, Fellow IE (India), and Senior Member IEEE. He has diversified research interests in the areas of Renewable Energy, Power Systems and Smart Grid.