Turkish Online Journal of Qualitative Inquiry
Volume 12, Issue 5, June 2021: 5085-5108

Research Article

A New Integrated Control Strategy of ANN-GA Based High-Power Quality Improvement in AC Micro Grids

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Abstract

This article develops a smart grid system by combining the two individual microgrids using electronically coupled distributed energy resources (EC-DER) inverter and smart impedance (SI) converter. Thus, the optimal power flow was achieved based on the each individual microgrid available power. The two “parallel optimization” methods are used to optimize various power quality challenges such as operation mode transfer transients, harmonic load sharing and parallel control of current and voltage quality. Thus, artificial neural network (ANN) approach is used for improving EC-DER performance and genetic algorithm (GA) is used for improving SI performance. The stability of the system is achieved by operating the ANN-GA in parallel processing manner. Thus, two microgrids develops the individual powers and optimal power flow is generated in smart grid. The simulation results shows that the proposed ANN-GA controller results the reduced total harmonic distortion (THD) and fault setting time in microgrids as compared to the conventional model predictive control (MPC) approach.

Keywords: *microgrid, total harmonic distortion, smart impedance, artificial neural network, genetic algorithm.*

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Received: 30.04.2021, Accepted: 04.06.2021

Introduction

The power supply process has changed rapidly as it mainly depending upon the micro-grid technology and distributed power supply. The microgrid [1] allows the development of renewable energies with higher capacity and it will not disturb the original power distribution network. But the microgrids are suffering with the EC-DERs controlling mechanism. Thus, the development of control system plays crucial role in EC-DERs [2] and maintains the energy balancing, appropriate transition between operational modes and providing acceptable power quality along with maintaining the economic operation. Thus, to achieve this objectives, various types of conventional approaches were developed in the literature. The controllers are mainly classified as linear and non-linear methods. The hysteresis voltage control (HVC) [3] is the one of the best non-linear mechanism. But it is failed to track the maximum power flow in EC-DERs. Also, the HVC requires the higher switching frequency for perfect operation, and it also contains changeable switching frequencies. Thus, the resonance problem was created resulted in the reduction of converter's efficiency in EC-DERs. To overcome this problem, linear controllers are developed with the constant switching frequency. Thus, the sliding mode control, linear quadratic controller (LQR), repetitive-based controllers, multi-loop feedback control, space vector modulation (SVM), deadbeat control and proportional-integral (PI) controller with pulse-width modulation (PWM) based linear controllers [4] were used. But the linear controllers were resulted in the huge amount of THD and caused to weak dynamic response. Similarly, the deadbeat control mechanism suffers with the parameter perturbations, measurement noise and fast transient response uncertainties for high sampling rates scenario.

Thus, it was not simple to design and accurate controller, because they need to fulfill the heterogeneous and diverse goals. To maintain both the goals [5], MPC controllers were developed for the EC-DERs and better results were obtained. MPC has plenty of advantages with least disadvantages as compared to the conventional approaches mentioned above. The drawbacks presented in the MPC overcome by the technology advancement with increasing speed of hardware. The major advancement of MPC system [6], its controlling flexibility in complex and non-linear systems. Here, the reference signals are monitored and tracked by using weighted cost function. Anyhow, the perfect selection of weights is still challenging task. Thus, it is necessesity to maintain and improve the power quality in microgrids is mandatory and it is achieved by improving the inertia and reducing the short circuit levels. In [7] authors developed the MPC based EC-DERs and reduced the short circuit current magnitude control by using the grid-connected (GC) and stand-alone (SA) mode of operation.

But it needs to optimize more with considerable research should perform on it. This work is mainly focusing on reduction of power quality of issues. Mainly weaknesses were observed, Harmonic and Linear load sharing nature of various loads and its problems were not discussed, and Damping resistors were utilized in series connection series with the filter capacitors for resonance reduction. In [8] authors gave an overview about microgrid structures and control techniques at different arranged order of levels. The focus was given on grid forming, grid-feeding and grid support configurations based out of droop control systems. In general, microgrid is formed by DGs, Electrical energy storage devices, interconnect loads with the objective to work on both modes i.e., on and off grid modes. Implementation of integrated communication methods between DGs and loads is no longer a challenge with development of hierarchical control systems. It gives a flexibility to perform well coordinated interaction for controlled operations and management with effective integration. In [9] authors gave insights of one of the control strategies called synchronverters which are nothing but inverters that act as synchronous generators. This configuration of control strategy focuses only on harmonics mitigation but create complex hardware which increase the cost linearly, therefore this kind of control strategy is not preferred. If loads are considered linear this problem, do not have any significance but in practical loads are mostly nonlinear and while load sharing harmonics issue comes into picture. In [10] authors described about harmonic power sharing and harmonic compensation via point of common coupling voltage in islanding mode by virtual harmonic impedance which first considers droop relation between harmonic impedances of DGs, and other power capacity converters then virtual harmonic impedance is introduced that combined with remaining power capacities of droop relationship forming the control technique for DGs to island mode. In [11] authors proposed a new technique parallel connected three phased converters for nonlinear load sharing without any communication between the converters. It also gives a solution for distinguishing between harmonic load currents flow and harmonic currents circulating among converters. The fundamental concept used by the authors is connecting ac power in parallel. This concept gave an equal sharing among linear and nonlinear loads. In [12] authors proposed a novel control strategy to get succeed with current harmonic sharing directly by controlling the inverter impedance which does not affect the voltage quality. In [13] authors addressed inaccuracy in harmonic load sharing in islanding mode. Authors proposed an enhanced droop control through online virtual impedance adjustment. DG reactive power, power imbalance power, is added to conventional droop control strategy, transients captured by this variation is balanced by fine tuning of the online virtual impedance. With proper regulation of fundamental harmonic frequencies at steady state accurate power can be achieved. In [14] authors proposed a technique which uses smart impedance in quasi-infinite busbar to transform to high impedance microgrid. Usually, hybrid active filters are used to address harmonic compensation with good filtering rate at low cost but results in voltage distortion. Authors proposed a smart impedance to use along with hybrid active filter to transform the two quasi-infinite bus, without any change of active power of the microgrid. This configuration can mitigate harmonic currents and voltages at resonance. It results in preventing voltage degrading at PCC.

To mitigate resonance, filter capacitors are used in series with damping resistors, which produces wideband and variable switching frequency. It increases overall system loss apart from slowing down the system dynamics control of EC-DERs. In [15] authors proposed an analytical approach based on impedance and explore it for balanced three phase mesh network with multiple LCL and LC filters. Nodal admittance matrix derives impedance ratios for different inverters which contribute to overall harmonic stability of the system. Valerio In [16] authors presented stability assessment of converter system based out of Eigen values and Harmonic Impedance estimation which is based on Linear Time Periodic systems theory. This proposed system by authors has an advantage of stability analysis done injecting small scale signal current by measuring disturbed quantities. In [17] authors presented a different state feedback approach for Finite Control Set MPC (FCS-MPC) system with LCL filter. Line side current control, two multi variable control approach and converter current feedback are considered as feedback control loop. Active damping methods and practical implementation problems are also discussed by the Authors. This system resulted in multi variable control and reduces switching and harmonic loss. This multi feedback systems have some disadvantages but have potentially alternative to traditional PWM based control systems. In [18] authors emphasize on load currents spectrum based on predictive current control technique. This technique predicts the practices of current for all possible voltage vectors. Every signal prediction is calculated using a cost function which makes to nearby value of desired system. Current Spectrum is altered with load errors and filters. The load spectrum can be shaped perfectly depending on the design of filter tune value. In [19] authors presented a different method which injects required power quality under variable grid condition, improves stability by active cancelling grid impedance using series active filter concept which reduces the grid disturbance. Due to this cancellator technique resonance levels are reduced between inverter and grid.

In [20] authors presented grid forming and grid support gird forming change in control strategies for near perfect smooth transition between grid connected to islanding mode and vice versa. Droop control and voltage frequency control is considered for calculation purpose of cost function which ensure methodical power share in the microgrid. To limit overcurrent and fault output current a complementary control is proposed. This work gives the stability of island mode and grid supporting grid feeding inverters and synchronous generators using small signal analysis. Inverters are enabling the functions which provide seamless transition of microgrid. Classifying between actual feasible condition and economic values derivation is explained by the Author. In [21] authors presented difficulties and uncertainties associated with transition of microgrid and propose more robust techniques in future research for more reliable and feasible economic system to address power quality issues during transition modes of microgrids. In [22] authors presented a hybrid control system for parallel control of current quality and voltage quality. It is especially important task as one cannot compromise on both parameter qualities. Traditional droop control technique does not guarantee voltage control within permissible limits. If even though voltage quality is ensured but EC-DERs current control is not possible. But this hybrid control system is based on the weights which vary and cost function of this quantities in an adaptive manner. This hybrid control mode (HCM) controls DG unit and fundamental harmonic frequency. In [23] authors proposed another flexible enhancement of power quality with use of hybrid current and voltage adaptive controller. It reduces the bandpass and low pass filter units in controller system. This proposed strategy reduces the complexity of DG control system without much effect on harmonic mitigation spectrum. Simultaneous voltage-controlled method and current controlled method are implemented using LCL filters and harmonic compensation filters by this hybrid control method. Even during frequency deviations, we can achieve effective and praise the qualities of both current and voltage.

In [24] authors gave detailed description about application of FCS-MPC to Power Electronic Converters and discussed comparison with traditional control techniques. FCS-MPC has a different approach to model system which predicts the next behavior of the variables. Prediction is basically based on cost function and it automatically frame sequences to minimize the cost function for next control action. Only initial value is applied in sequence, algorithm train itself for next values in given sampling period. This system becomes complex for large systems. A possible solution is taking advantage of finite switching states of converters which can be selected for possible minimum cost for this switching states. In general, traditional linear control system with modulation are limited due to limited feedback structure. Whereas FCS-MPC due to its predictive nature feedback is more efficient which includes cost function as well and is not limited to error magnitude of the variable in control. In [25], the authors developed distributed power generation system by maintaining the economic operation with respect to both the input and profit, it was achieved by adopting the particle swarm optimization (PSO) in controllers. In [26], hybrid Gaussian mutation with PSO was used to get the maximum profit in microgrids, respectively. To achieve the better controlling operation, in [27] authors adopted the Quantum Genetic Algorithm (QGA) for active control of micro-grid operation with uncertainties removal. But still hierarchical management problems were presented. To solve these problems, in [28] developed the modified GA for distributed management system problem optimization and low pollution with high efficiency was achieved by perfect usage of scheduling algorithm. In [29], a novel distributive power generation and transmission system was developed based on the optimal pollution treatment and operating cost. Here, to optimize the THD, Modified harmony search was used. Harmonic load sharing for nonlinear and linear loads, Resonance effect due to damping resistors and filter capacitors which reduces control dynamics of EC-DERs, Smooth transition of microgrid modes, simultaneous control of current and voltage qualities and proper load share between EC-DERs are the major problems effecting the microgrid system [30]. From above studies, it is observed that the by using optimization algorithms, all kind of linear and non-linear effects generated in the MPC based EC-DERs can be effectively eliminated and improves the power quality. It was seen from review works before that few major problems are still to be answered. To solve these problems, this work is contributed as follows:

- A smart grid is designed by combining the optimal power flow from two individual microgrids with EC-DERs and SI.
- The optimal performance of EC-DER is achieved by using the ANN controller, as it develops the accurate gate pulses with optimal weights for voltage quality improvement.
- The operation of SI is optimized by utilizing GA, the combined cost function is developed for both ANN-GA to solve the optimization problem in parallel processing manner.
- The ANN-GA controllers are worked in parallel manner and reduced the THD by 18% and fault setting by 0.3 seconds as compared to the conventional MPC controller [24].

Rest of the paper is organized as follows: Section 2 deals with the detailed analysis of EC-DER controlling by ANN. Section 3 deals with GA operation for controlling the SI. Section 4 deals with the operation proposed ANN-GA controller in smart grid systems. Section 5 deals with the simulation analysis with the various scenarios. Finally, section 6 concludes the article with possible future enhancements.

ANN Controller for EC-DER

This section gives the detailed analysis of the ANN controller for the proposed EC-DER inverter.

ANN architecture

The ANN plays the crucial role in real world control systems for improving the operation and for acquiring the desired operation. ANN is the advanced artificial intelligence mechanism; it has the capability to optimize any system by the perfect end to end such as input to output training. To achieve the accurate outcome, ANN was developed with the multiple number of hidden layers and these layers are interconnected by the weight maps. Feed-forward model of ANN network does not consist any loops, so it consumes lesser memory or memoryless in in-out mappings. Finally, the mathematical model of Feed forward based ANN model is represented as follows:

$$F(\vec{x}) = h(w_0 + \sum_{i=1}^{M} w_i . x_i) \quad (1)$$

Here, $h(x)$ indicates the nonlinear activation function, normally it used either hyperbolic tangent or logistic sigmoid to perform the activations. $\vec{x}$ is the input data and contains $\{x_1, x_2 \ldots . x_M\}$ range with M number of samples. Each element x_i contains its own weights w_i. The correction or bias factor is indicated by the weight w_0 respectively. This work utilizes the "shallow" type feed-forward ANN model. thus, it is functioned based on the multilayer perception. Thus, lesser number of hidden layers are enough to implement the controlling strategy with less memory consumption. Based on the number of input and output variables, then the input and output layers are configured to perform the application specific operation. The cost function of EC-DER is improved by using the ANN training and testing. Thus, the optimal weight coefficients (w_i and w_0) are identified by using the ANN training procedure, respectively. The smart grid based tuning procedure was introduced for accurate selection of optimal controlling features by using 20 units in each hidden layer. To achieve the best conjugate gradient optimization, then the training was performed by using Scaled Conjugate Gradient (SCG) with high level convergence properties.

ANN training procedure

To train the network, the Neural Network (NN) Fitting tool is considered. Thus, the predicted values of reactive and harmonic powers were calculated by using pretrained ANN model. So, the training of ANN must perform in careful manner to achieve the optimal values. The NN tool considered the 60% of data (DFT output) samples for training, 20% of data samples for validation and 20% of data samples for testing. the ANN training process deals with 20 weights in single hidden layer which are assigned for the controller i.e., (1,0) to (1,20), to perform the better output function for improving the performance of grid connected EC-DER system.

ANN-based controller

For training and testing of ANN, multiple input parameters are considered from the outputs of DFT, they are filter current ($i_{sabc}(k)$), output voltage ($v_{sabc}(k)$), output current ($i_{dc}(k)$) and reference voltage ($v^{*}{}_{c}(k)$) generated in the EC-DERs system. Here k indicates the training and testing sampling time with gain. The ANN generates outcome as optimal voltage vector x_{opt} respectively. This optimal output voltages are applied as input to the IGBT inverter bridge and results the output as three switching states S_a, S_b and S_c. The ANN based controller was trained with the offline collected MPC samples. After perfect training operation, the trained ANN will replace MPC in figure 3 and results in the accurate controlling strategy. The ANN based controller for IGBT inverter bridge with three phases is presented in the figure 1, respectively.

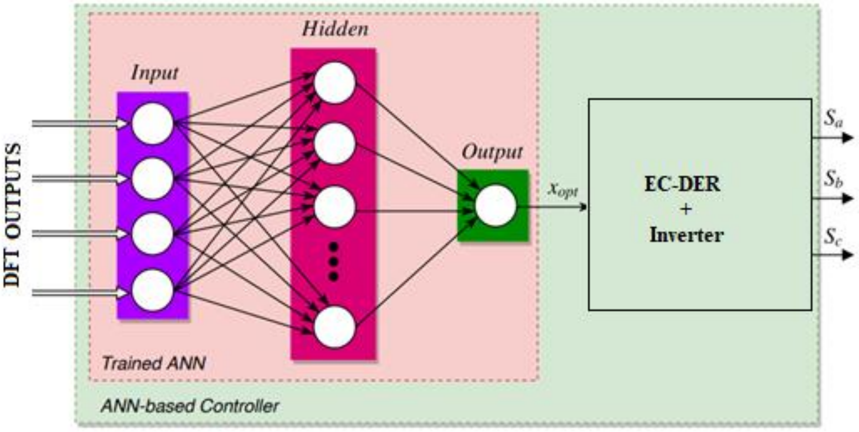


Figure 1: Block diagram of the proposed ANN-based controller for EC-DER inverter.

Thus, it results in the high-quality output sinusoidal voltage with through the LC filter and reduces the THD for the different load combinations. The controlling mechanism of ANN controller for each sampling time k is described as follows:

- Calculate the voltages and currents $i_f(k)$, $v_c(k)$, $i_o(k)$ for each sampling time k. Here, $i_o(k)$ is the measured value of EC-DER.
- By additionally considering the $v^*{}_c(k)$ along with $i_f(k)$, $v_c(k)$, $i_o(k)$ for training of ANN, will results in reducing the distortions and generates the x_{opt} perfectly without losses. Then, this x_{opt} applied to the IGBT universal bridge of EC-DER inverter.
- Finally, the inverter generates the perfect switching states $S_a, S_b\ and\ S_c$ for fast convergence operation. These switching states are used maintain optimal weights λ_V and λ_i. So, it will reduce the fault detection time.

GA Controller for SI

Basic operation of GA

This section deals with the implementation of GA for optimal power flow in the SI. Thus, it will improve the operational characteristics under the perfect network scenarios. Thus, both non-critical and critical loads are perfectly needed to monitor. In real world scenarios, 30% loads need the uninterruptible operation, thus it requires a critical optimization method in smart grids. Thus, to solve the design problems, the GA was developed to achieve the lower computational complexities. GA inhibits the more benefits such as global search capabilities compared to conventional evolutionary and programming approaches presented in literature. It is already proven that GA is perfectly applicable to both linear and non-linear systems of Microgrids based storage and renewable generation process. Here, GA is developed on the properties of mimic's natural biological procedures and global search metaheuristic. The basic operation of GA is described as follows:

- Generates the optimization problem along with potential solutions.
- The initial population is developed according to the solutions. The population are developed from user-defined and randomly selected values.
- For the microgrids, conventional evolutionary algorithms need the greater number of fitness functions and unable to stop the iterative process, as there is no perfect solution achieved. By using GA, the fitness or evaluation function is used for analyzing the potential solutions based on the problem "fitness" levels with less iterations and stops at least Fault setting time in SI.
- Then, mutation and crossover based Genetic operators continuously changes the changes the compositions of chromosomes and resulted enhanced optimization. Thus, the various controlling of SI based microgrids is achieved.

Genetic Algorithm operation in SI

In this work, GA is used to identify the optimize the system with optimal weights λ_V and λ_i. Thus, the optimization problem was developed to calculate the initial weights, thus the overshot and Fault setting time is reduced effectively. Finally, the optimization procedure reduces Fault setting time as much as possible and also controls the overshoot amplitude. Figure 2 presents the flow chart of GA with four major steps of operation.

Step 1: Initialization of Parameters such as bio-inspired operators, population, maximum generation, and population size.

Step 2: The matrix was created from every induvial population value. These matrices are applied to the SI of microgrid through Simulink modelling.

Step 3: After initial simulation, basic Maximum amplitude and Fault setting time are obtained. Then total fitness value $F(X)$ is generated by using these vectors. The multi-objective optimization function of GA is given as follows:

$$F(X) = \begin{cases} \sum_{i=1}^{3} S_i . T_i(X) , \ X \in G(X) \\ \sum_{i=1}^{3} S_i . T_i(X) + (\beta . C) , \ X \equiv G(X) \end{cases} \tag{2}$$

Here, X was the optimal solution vector of GA. $T_1(X)$ is objective function for resistance, $T_2(X)$ is objective function for step voltage and $T_3(X)$ is objective function for grounding grid touch voltage. The fitness constraint condition is denoted by $G(X)$, penalty function is denoted by the β and maximum constant is denoted by C.

Step 4: To achieve the best fitness values, bio-inspired operators, selection, crossover, and mutation are continuously updated. The steps 2-4 performed in iterative manner. Thus, the minimum optimization problem will be achieved. The minimal optimization problem generated from the iterative update process as follows:

$$T_{min}(F(X)) \text{ s. t. } \quad X \in G(X) \in [R_L, R_U] \tag{3}$$

The minimum fault setting time is indicated by $T_{min}(F(X))$. Here, X was the updated prominent solution vector of GA and it updates the weight coefficients λ_V and λ_i with lower boundary R_L and upper boundary R_U. By using these boundaries, the optimal weight coefficients are “selected” for each objective function. The best weight coefficients are generated by identifying the “crossover” relationship between each objective function with respect to population.

Here, the crossover process considers only population, that satisfies the stochastic uniform probability (Crossover probability). If any small error in the weight coefficients occurred, then by using the “Mutation” process every population adjusted accurately. Here, the mutation provides the genetic diversity and capable of searching optimal solutions of weight coefficients in wider population space.

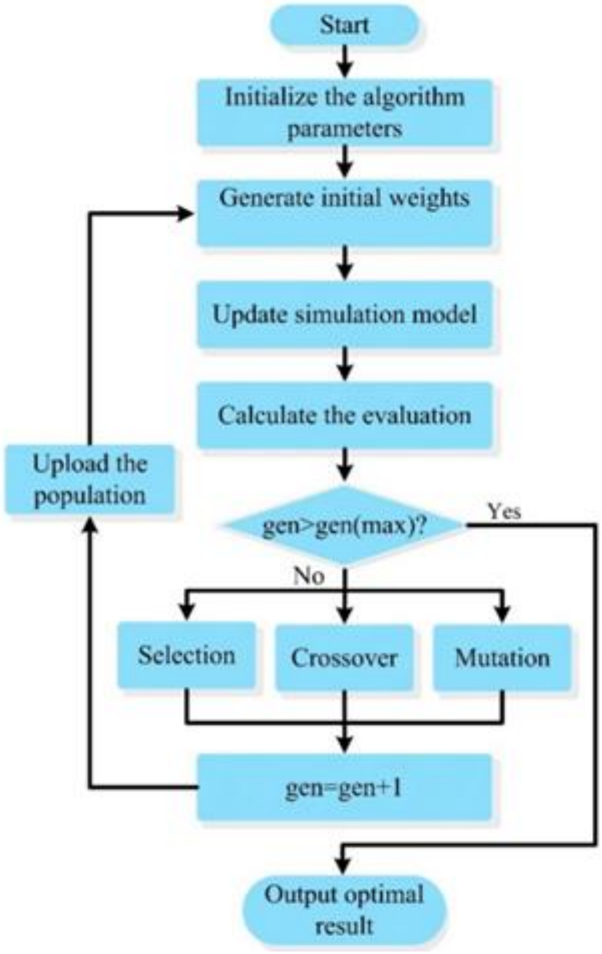


Figure 2: Flow chart of the GA for SI.

Here, mutation operation performed in “gaussian” nature. Then, final optimal weight coefficients are generated as follows:

$$\lambda_V = \begin{cases} 1, & \mathrm{T}_2 > \mathrm{T}_{2\_save} \\ 0, & \mathrm{T}_2 \le \mathrm{T}_{2\_save} \end{cases} \tag{4}$$

$$\lambda_i = \begin{cases} 1/L, & \mathrm{T}_i > \mathrm{T}_{i\_save} \\ 0, & \mathrm{T}_i \le \mathrm{T}_{i\_save} \end{cases} \tag{5}$$

Here, best fitness function is denoted by L and maximum allowable values is T_{i_save}.

Proposed ANN-GA based EC-DER control strategies

EC-DER's control strategies

The EC-DER inverters play the major role in the micro grids, to achieve the robust, flexible, and optimal operation with reduced fault detection time. Recently, Grid-support-grid-forming, Grid-support-grid-feeding, Grid forming and Grid feeding based control strategies were introduced to achieve the optimal operation of microgrids. But these control methods were suffering with operation mode transition problem in the microgrids. Thus, an unwanted transition is generating by planned or faults in system. Normally, grid-forming method supports island mode and grid-support–grid-forming method supports both GC and island operational modes. But these two methods are failed to provide the either stable frequencies or stable voltages for the microgrid. Thus, these two methods need to utilize along with grid-support–grid-feeding and grid feeding control strategies for effective operation. Again, these combinations make the control system extremely complicates and consuming more power and time. Thus, to improve the microgrid performance, the control strategies of EC-DERs needs to update continuously. Here, the grid-feeding control mechanism used widely because it aims to maximize the energy export also provides the best profit. In this method, reactive and active reference powers and reference currents were usually obtained by using the optimization methods. The well-known optimization used in this controlling mechanism is maximum power point tracking. But it has the limitation of increasing fault detection time and increasing THD. Here, the reference power (or current) will be injected into microgrid by the EC-DER for appropriate measurement of phase angles and amplitudes. Generally, the maximum power will be injected into microgrid by the EC-DER user and assigns the set point reactive power to zero. Thus, this method does not support frequency and voltage changes in the network.

Usually, industrial networks need the uninterrupted power supply, thus the Grid-forming control strategy is used to achieve this with isochronous operation. In grid-forming, the reference voltage is calculated by using phase angle, frequency, and amplitude of the microgrid. Then, the EC-DER continuously monitors the reference voltage. Thus, this continuous monitoring of voltage leads to more time consumption. To overcome this problem, grid-support–grid-feeding control strategy was developed with advancement of grid-feeding. In this mechanism, droop control system is used to regulate the reactive and active powers and shares these powers to EC-DERs. Grid-support–grid-forming control method also developed from the basics of grid-forming approach. This method is tremendously popular as it supports both GC and island modes of operation. In this method, reactive and active reference powers and reference currents were usually obtained by using the optimization methods. This work mainly focused on development of smart grid system, which was developed from individual microgrids using EC-DERs and SI. Thus, ANN-GA controller is used in this work to achieve the optimal performance of smart grid. The detailed system architecture of EC-DER inverter with ANN-GA controller is presented in the Figure 3.

Perfect reactive power and harmonics compensation in EC-DER system is achieved by using the ANN-GA controller. In EC-DERs, mismatch of non-linear loads is usually occurred as renewable energy sources (RES) are directly connected to microgrid. The ANN-GA controller has the capability to adjust the generated reference current automatically for all the types of variations. The variations are usually occurred in voltages, currents of the integrated RESs, grid tariff and source current. Thus, the non-linear load systems are perfectly balanced by the ANN-GA controller. To achieve this, the ANN-GA operates in three modes of operation based on gain values. These gain values are estimated by introduction the three distinct system conditions. The conditions are voltage level, battery current availability of source and RES conditions. Apart from modes of operation, the ANN-GA controller also considers the seven scenarios to improve the voltage issues in the system. They are (i) Supervise one irrelevant load and one critical load, (ii) Supervise four irrelevant loads, (iii) Supervise one individual critical load, (iv) Supervise two critical loads separately, (v) Supervise two dynamic loads separately, (vi) Supervise the grids operation and (vii) Supervise all the loads operation. Based on accurate mode selection and scenario selection by ANN-GA, the compensation current is generated by using the optimal weights λ_V and λ_i.

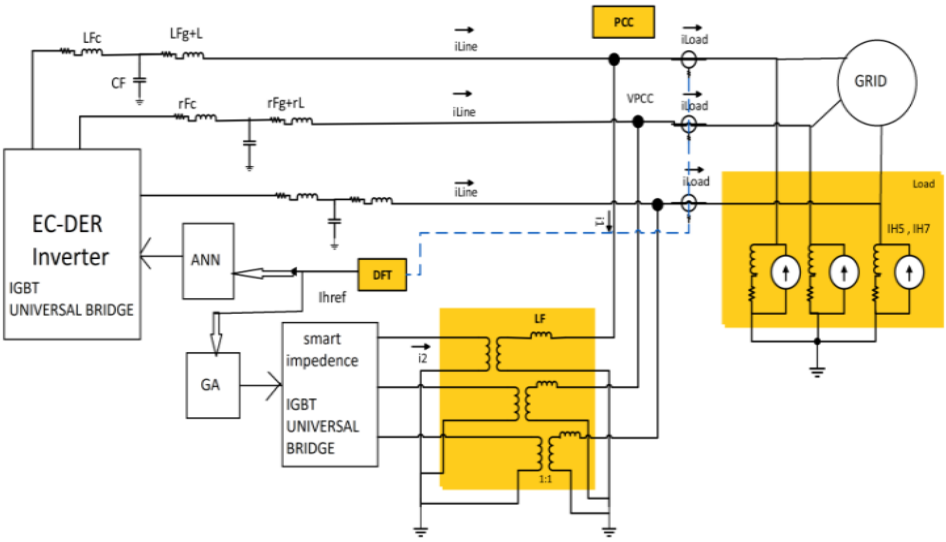


Figure 3: Proposed ANN-GA based EC-DER system

EC-DER and SI for harmonic flow control

If a non-linear load is connected to the EC-DER, then the EC-DER generates both lower and higher line impedances. The increment in the distortion power supply results in the overload of lower line impedances, whereas higher line impedances maintain the constant load. Further, to control the overloads, load changes and harmonic load sharing, the proposed system needs an optimal control mechanism. Thus, non-linear also gets the proper supplies. Even though, SI providing the short circuit path for effective harmonic power flow, SI additionally needs the GA based optimization of power flows and EC-DERs needs an additional controller. Both the ANN and GA optimization techniques are executed in parallel manner, so fast convergence to individual EC-DER and SI will achieve effectively.

The ANN controller has improved stability and faster transient response as compared to the conventional FCS-MPC controllers. So, it is perfectly suitable for controlling of the EC-DERs. The ANN-GA method was utilized for optimizing and solving of harmonic instability glitches and harmonic load sharing problems presented in the microgrids, respectively. Here, the EC-DER is controlled by the optimal gate pulses generated from the ANN controller with grid-support–grid-forming properties and SI operation is optimized by the GA. Thus, EC-DERs optimal reference voltage is calculated and resulted in the reduced harmonics as compared to conventional FCS-MPC mechanism.

This paper also presents the GA based optimization method for effective control of SI and it is connected in sequential manner with load, respectively. The exact harmonic spectrum is generated and controlled by the SI.it means, the SI functions as bypass path or short-circuit shunt for the applied frequencies. Similarly, SI acts as open circuit for the unknown frequencies. Thus, distortion power flow will be reduced in the inverter and line capacities and archives the higher economic justification. Also, PCC acts as infinite bus if the harmonic power flow is either eliminated or reduced and PCC voltage level also enhanced. The entire performance of SI is analyzed by using equations (6)-(8) and parameters and variables of this equations are presented in table 1. The current difference equations are leading the SI operation is denoted as follows:

$$i1_{(k+1)} = E\left(\left(\frac{T_S}{A}\right)\left(V_1(k) - \left(\frac{L_m.V_{dc}}{B}\right)\right)\right) + i1_{(k)}\left(\left(1 - C\left(\frac{T_S}{A}\right) + \frac{L_m(R_m.T_S - L_m)}{A.B}\right)\right) + i2_{(k)}\left(\left(\frac{-R_m.T_S + L_m}{A} - \frac{L_m(1 - D.T_S)}{A.B}\right)\right) \tag{6}$$

$$i2_{(k+1)} = E\left(\left(\frac{T_S}{B}\right)\left(V_2(k) - \left(\frac{L_m.V_A}{B}\right)\right)\right) + i1_{(k)}\left(\left((-R_m.T_s + L_m) - \frac{L_m(1-C.T_S)}{A.B}\right)\right) +$$

$$i2_{(k)}\left(\left(1 - D\left(\frac{T_S}{B}\right) + \frac{L_m(R_m.T_S-L_m)}{A.B}\right)\right) \tag{7}$$

Here, A, B, C, D and E are resistance and inductance coefficients. They are given by

$$A = L_{l1} + L_m + LF\ ,\ B = L_{l2} + L_m,\ C = r_1 + R_m + R_L,\ D = r_2 + R_m\ ,\ E = \frac{AB}{AB-L^2{}_m} \tag{8}$$

The following cost function is considered for the development of short circuit path for perfect flow of current harmonics and resulted in reduction of harmonics.

$$g_{THD} = \left|real\left(i1_{(k+1)} + ihref\right)\right| + \left|imag\left(i1_{(k+1)} + ihref\right)\right| \tag{9}$$

Here, load current harmonic content is indicated by the $ihref$, it is generated from the Discreet Fourier Transform (DFT). Then, $i1_{(k+1)}$ is assumed primary current of transformer, which will generate at (k+1) sampling time, respectively. This current will be controlled by the SI through GA, which controls the dc voltage presented in transformers secondary side. Finally, it is observed that SI with GA is successfully eliminates the harmonics presented in the line current and this signal now can be treated as the reference signal. Thus, the SI with GA successfully prevents the load mismatches and harmonic instability presented in microgrid. Furthermore, the harmonic instability generated in the EC-DERs also eliminated by perfect controlling switching frequencies by the ANN. Thus, the harmonics generated in frequency droop control dynamics and load side harmonic sources also reduced in the microgrids with the parallel operation of ANN-GA.

Simulation Analysis

The simulations are performed by using the MATLAB/Simulink software and the entire structure of EC-DERs with ANN-GA controller is presented in the Figure 4, respectively. It is a simulation model integrated 3-bus grid and load connected. Figure 5 represents the ANN-based hybrid control of voltage and current fed EC-DER inverter system and Figure 6 represents the GA-based hybrid control of voltage & current fed SI inverter system.

Figure 7 represents the current waveforms generated by using the existing MPC controller in EC-DER1 and EC-DER2 systems. From the figure, it is observed that these currents are affected by the numerous harmonics as there is no SI system.

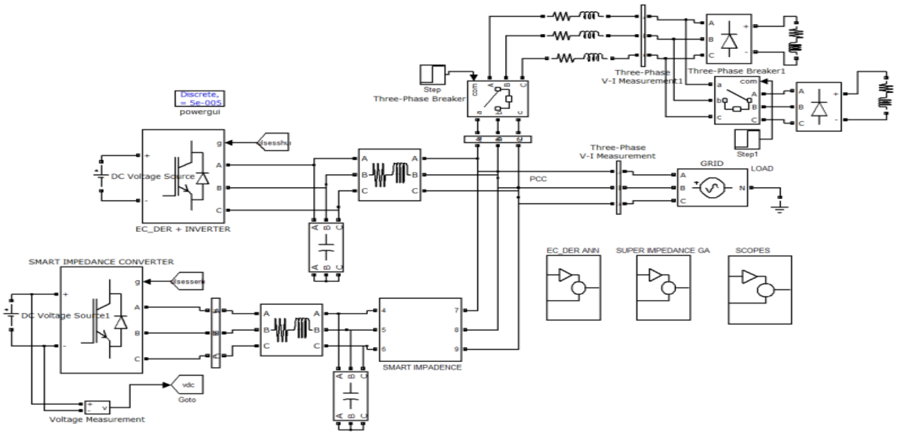


Figure 4: Simulation model of a proposed ANN-GA integrated 3-bus grid and load connected.

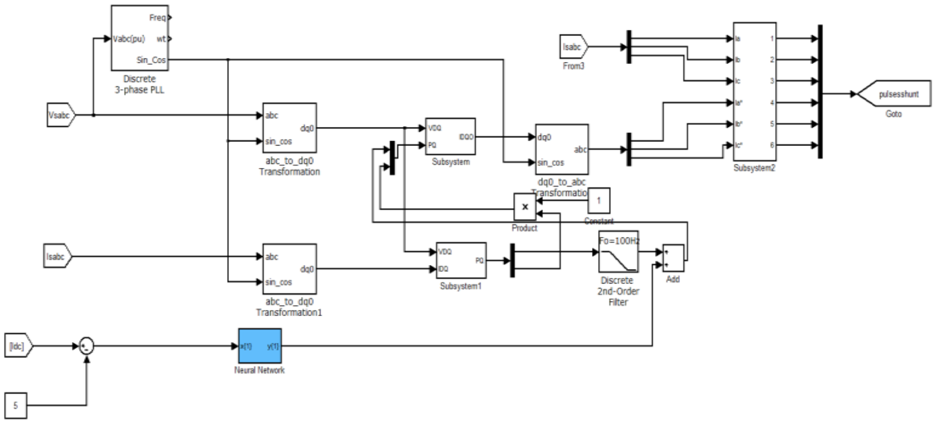


Figure 5: ANN-based hybrid control of current and voltage fed EC-DER inverter system.

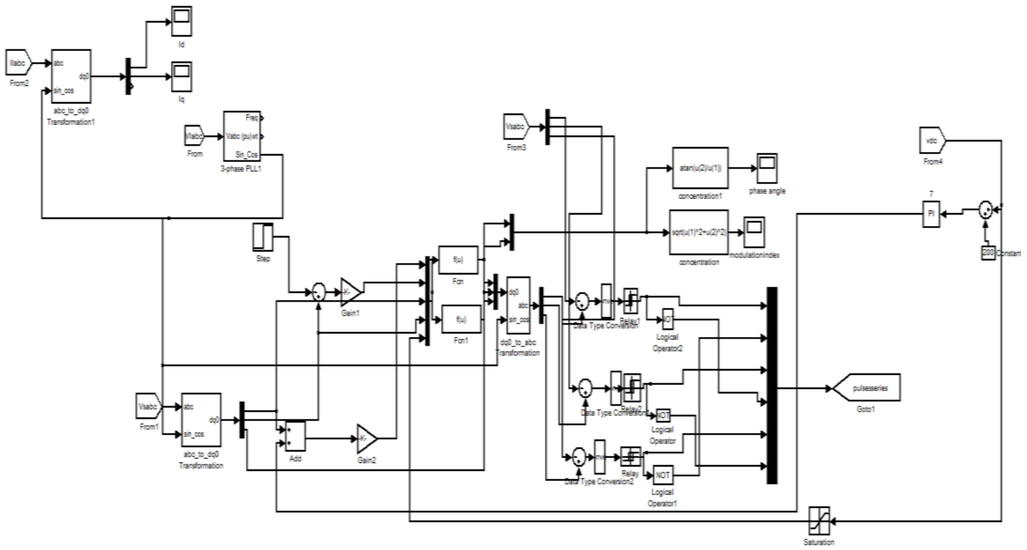


Figure 6: GA-based hybrid control of current and voltage fed SI inverter system.

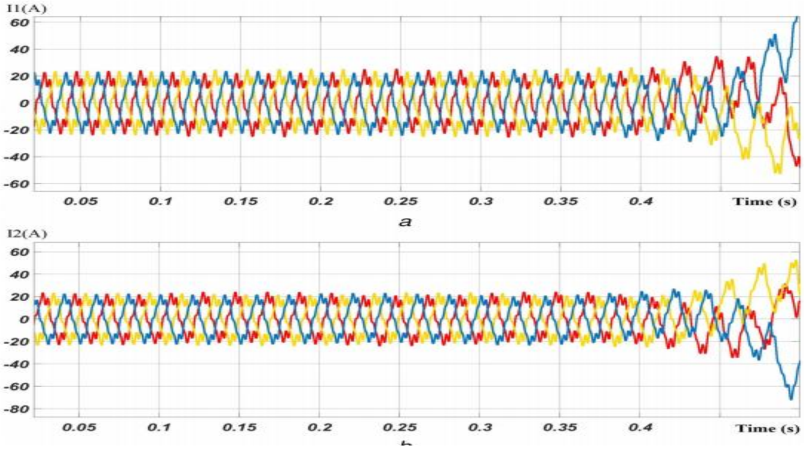


Figure 7: Conventional MPC based EC-DER1 and EC-DER2 current outcomes [24].

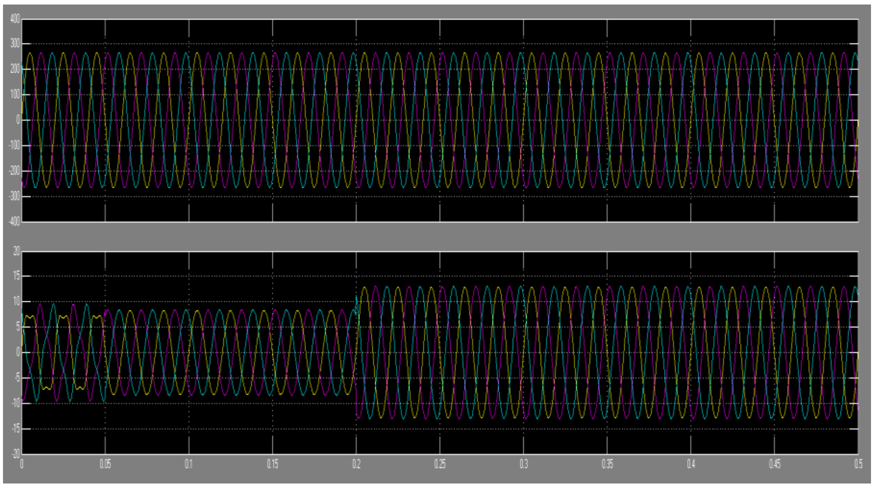


Figure 8: EC-DER1 and EC-DER2 current outcomes with ANN and GA.

From Figure 8 it is observed that, the ANN & GA combination bypasses the harmonics presented in load side and alters PCC operation to a quasi-infinite bus. In this manner, it neutralizes dangerous effects of interactions and coupling between various components of the micro grid and improves the performance as compared to the conventional MPC.

From Figure 9 it is observed that, the conventional MPC controller does not succussed in extracting the perfect harmonic current from the line current and it is unable to reproduce the accurate reference signal. By observing the zoomed waveform, there is a considerable difference presented between harmonic current SI reproduced current. This difference indicates still there existed switching ripples in the EC-DERs.

From Figure 10 it is observed that, the proposed method resulted in the better stability outcome as compared to the conventional MPC based micro grid stability. It is achieved by using ANN controller as it reduces the switching ripples presented in EC-DERs. The ANN has the capability to generate the faster switching gates pulses as compared to the MPC based controller. it is observed that the ANN controller successed extraction of various harmonic currents from the line current and it reproduces the accurate reference signal.

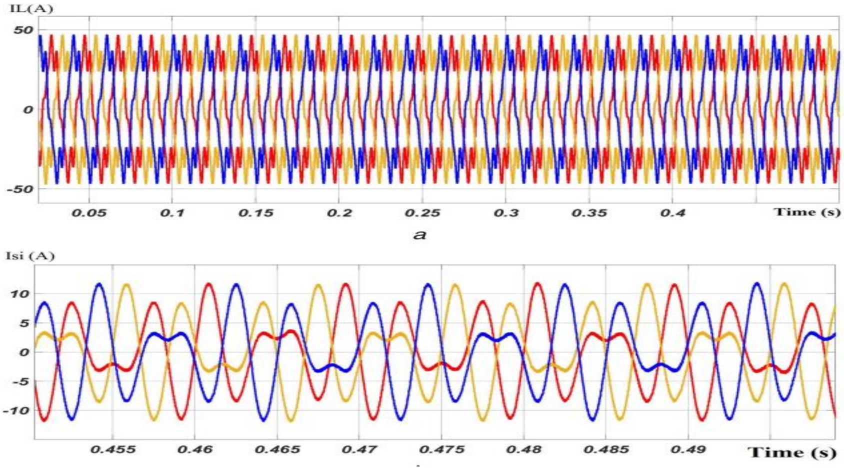
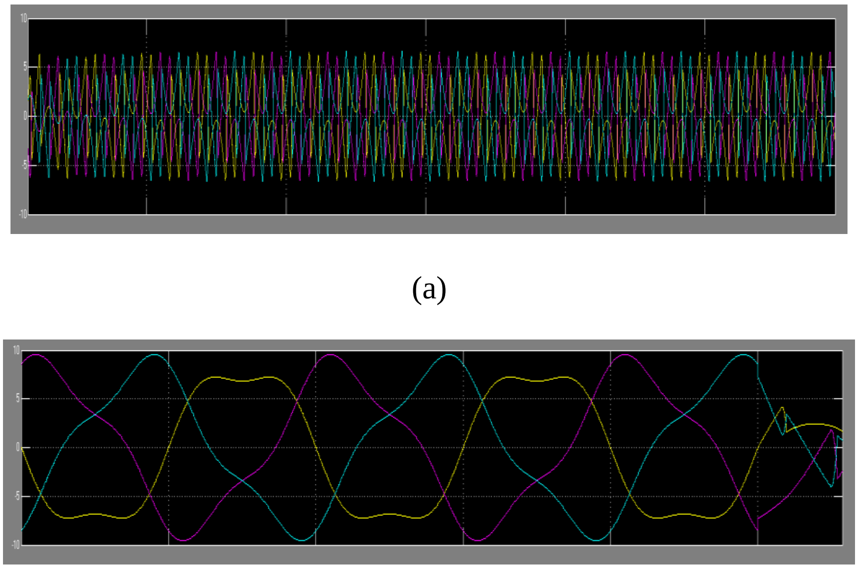


Figure 9: Conventional MPC based microgrid stability by utilizing SI [24]. (a) load current, (b) zoomed version of load current.



(a)

(b)

Figure 10: Improving micro grid stability by utilizing SI. (a) load current. (b) zoomed version of ANN-GA based load current.

Smooth transition among various operating modes analysis

This subsection presents the detailed analysis of the changing the transition among GC and island operating modes by using the new operation mode transition scheme. This method operates based on the event-controlled cost function, respectively. The circuit breaker is used to maintain the connection and disconnection between distribution network to the microgrid and it controlled by the ANN controller. Thus, the ANN controller monitors the exported/imported current generated from/to microgrid in GC mode of operation. The ANN controller also monitors the grid voltage in island mode of operation. The transients occurring in the transient time is limited by the state(mode) changing mechanism of circuit breaker and it continuously updates the cost function. The ANN controller cost function is given as follows:

$$g = \lambda_V \left|\left(\mathrm{V}_{EC-DER_3} - \mathrm{V}_{ref_{EC-DER_3}}\right)\right|^2 + \lambda_i \left|\left(\mathrm{i}_{EC-DER_3} - \mathrm{i}_{ref_{EC-DER_3}}\right)\right|^2 + \exp -\left(\frac{t-t_d}{\tau}\right)\left|\left(\mathrm{i}_{EC-DER_3} - \mathrm{i}_{ref_{EC-DER_3}} - IG\right)\right|^2 + \exp -\left(\frac{t-t_c}{\tau}\right)\left|\left(\mathrm{V}_{EC-DER_3} - V_{PCC}\right)\right|^2 \quad (10)$$

Here, attenuation constant is denoted by τ, connection time of grid is denoted by t_c, island time is denoted by t_d and exported/imported current from/to the microgrid is denoted by the IG.

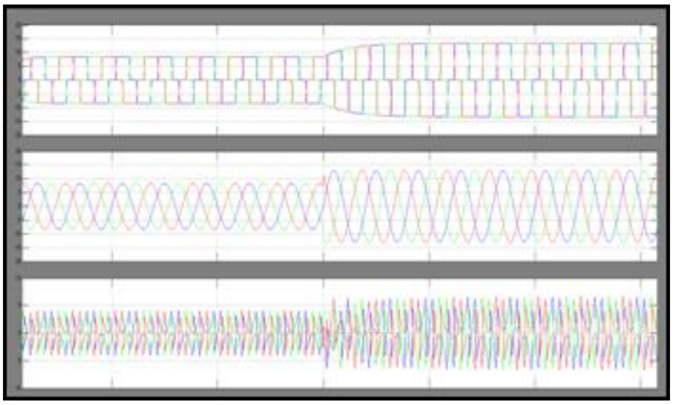


Figure 11: Performance of conventional MPC controller operating mode change from GC to standalone [24]. (a) 1st EC-DER current. (b) 2nd EC-DER current. (c) 3rd EC-DER current.

Figure 11 represents the different currents generated in various EC-DER with their operating mode changed from GC to stand-alone by using the conventional MPC controller. From the currents, it is observed that they are affected with huge harmonics as there is no perfect scheme for fast triggering of modes.

Figure 12 represents the current and voltage generated in first EC-DER for operating mode changed from GC to stand-alone by using the proposed ANN-GA controller. Under the normal situations, if there is no event then the circuit breaker status does not change, thus EC-DER1 is operating as the hybrid current and voltage controller (the first two terms in the cost function will monitor the entire EC-DER cost function). If the PCC's circuit breaker triggers, then disconnection between utility grid from the microgrid takes place and increases the weight factor (last two terms of cost function increase rapidly with an exponential factor 3), respectively. As a result, the overall controlling of EC-DER1 is achieved and results in the perfect voltage and currents without THD.

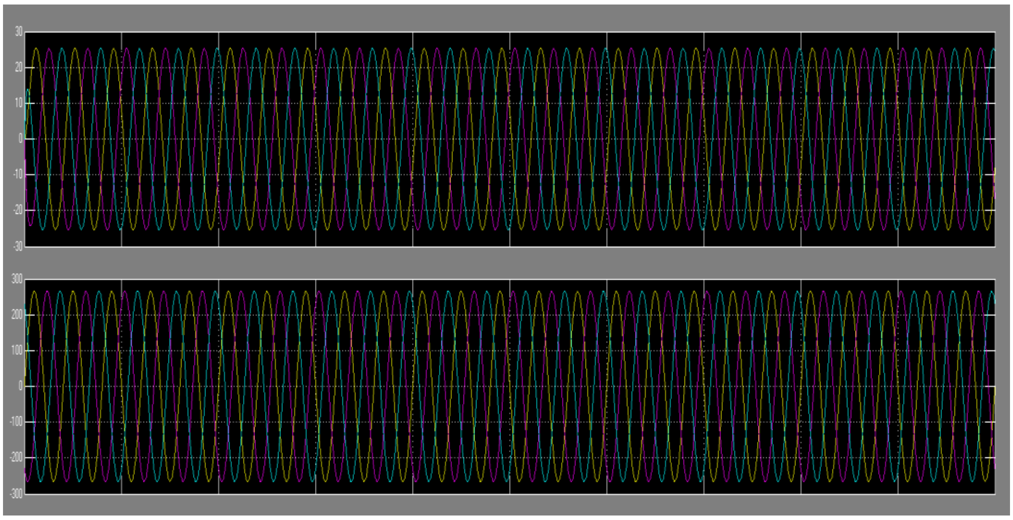


Figure 12: Performance of hybrid ANN-GA integrated in the 1st EC-DER. (a) 1st EC-DER output current (b) 1st EC-DER output voltage.

Harmonic spectrum shaping for resonance mitigation

To reduce the resonance in the EC-DER systems, the ANN controller generates the gate pulses in high-speed manner by using Harmonics spectrum shaping. As compared to the conventional MPC based passive damping method, the ANN based Harmonics spectrum shaping improves the system efficiency by reducing its losses. Thus, the EC-DERs is capable to react for fast gate pulses and transients. by using the SI Additionally, the resonance frequencies were also reduced. Thus, the ANN and GA operate parallelly along with reduction of resonance frequencies generated in the converter output. For this parallel operation, a novel hybrid cost function is defined as follows:

$$g = \lambda_V \left|\left(\mathrm{V}_{EC-DER_{i(k+1)}} - \mathrm{V}_{ref_{EC-DER_i}}\right)\right|^2 + \lambda_i \left|\left(\mathrm{i}_{EC-DER_{i(k+1)}} - \mathrm{i}_{ref_{EC-DER_i}}\right)\right|^2 \qquad (11)$$

Here, weight coefficients λ_V and λ_i are estimated from the ANN-GA controller. These weights are calculated to reduce the voltage THD (THD_v) and current THD (THD_i) presented in the EC-DER system with the usage of optimal cost functions. Generally, ANN-GA controller increases the λ_i for avoiding the harmonic uncertainties for accurate design of $\lambda_i - \mathrm{THD}_i$ based droop. The λ_v value is usually maintained high for reduction of unnecessary flowing currents. Anyhow, the ANN-GA controller was designed to maintain the perfect voltage and current quality under seven scenarios with three operating modes of microgrid. Thus, by perfectly maintaining both λ_i and λ_v resulted in the reduction of distortion power effectively and achieved 18% THD value as shown in figure 13.

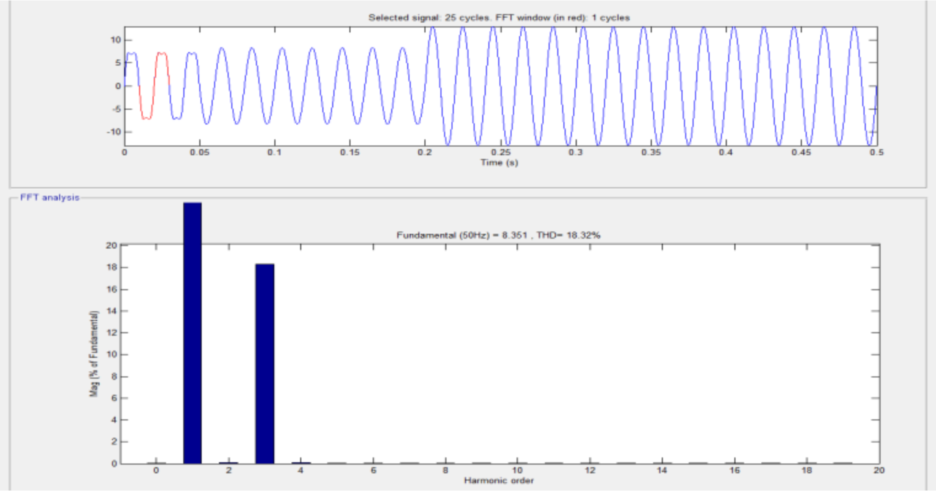


Figure 13: THD analysis of ANN-GA based EC-DER.

Table 1: Parameters and variables.

Variable	**Description**	**MPC [24]**	**ANN-GA**
r12 & r22	grid side resistance	0.02 Ω	0.02 Ω
r11 & r21	converter side resistance	0.04 Ω	0.04 Ω
IH5 & IH7	non-linear load in fifth & seventh harmonics (SI)	7A & 5A peak	3A and 5A peak
THD (in %)	Total Harmonic Distortion	26-30	18
Fault (in sec)	Settling time	0.5-0.6	0.3

Finally, Table 1 compares the conventional MPC controller with the ANN-GA controller in EC-DERs. Both the input resistance parameters and output THD and fault setting time are compared. From the comparison, it is observed that the proposed ANN-GA controller resulted in the reduced THD and fault setting time.

Conclusion

This work mainly focused on development of smart grid system, which was developed from individual microgrids using EC-DERs and SI. Thus, the optimal power flow was achieved based on the each individual microgrid available power. The deep learning-based ANN method was utilized for optimizing the operation of EC-DERs, similarly bio-inspired GA approach was used to improve the performance of SI. These, two optimization algorithms were developed and simulated in parallel processing manner, thus the power flow in two microgrids was generated parallelly. The enhanced cost function was developed by the ANN-GA controller for minimizing the resonance-based optimization problems and generated the weight coefficients. By utilizing this weight coefficients in EC-DERs and SI system, the THD was reduced in both currents and voltages and achieved the improved power quality. Finally, smooth transition among various operating modes with reduction of Harmonic spectrum shaping for resonance mitigation. From the simulations, it was proved that the proposed controller reduced the THD by 18% and reduced the Fault setting time to 0.3 seconds as compared to the conventional MPC based controller.

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