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The power quality supply is a major challenge in the distributed system. Moreover, the issues may occur due to the imbalance of power supply and harmonics and flicker with increasing applications in the distributed system. The main intent of this paper is to design an MC-UPQC to solve the power quality issues in the distribution system. The MC-UPQC involves two series Voltage Source Converter (VSC), where the power is transferred from one feeder to another to eliminate the "voltage sag, swell, interruption, and transient response." The hybrid meta-heuristic algorithm Beetle Swarm-based Butterfly Optimization Algorithm (BS-BOA) is developed by the combination of Beetle Swarm Optimization (BSO) and Butterfly Optimization Algorithm (BOA). The proposed BS-BOA optimizes the membership limit by the hybrid meta-heuristic algorithm, from which the control rules are generated for inputs. The major benefit of the optimized FLC-based MC-UPQC is its quick behavior in minimizing the Total Harmonic Distortions (THD). The comparative analysis was done over the traditional controllers to validate their effectiveness. From the analysis, the THD of the proposed BS-BOA-FLC-MC-UPQC is 99.99% better than BOA-FLC-MC-UPQC and 80% better than BS-FLC-MC-UPQC. Thus, the simulation result has outperformed the proposed method and has attained improved power quality.

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Optimal Operation of Multi-Converter-UPQC for Power Quality Improvement in Distribution System using Optimized Fuzzy Logic Controller

--Manuscript Draft--

Full Title:	Optimal Operation of Multi-Converter-UPQC for Power Quality Improvement in Distribution System using Optimized Fuzzy Logic Controller
Manuscript Number:	UCBS-2022-0758
Article Type:	Research Article
Keywords:	Multi-converter-UPQC; Distribution System; Power Quality Improvement
Abstract:	The power quality supply is a major challenge in the distributed system. Moreover, the issues may occur due to the imbalance of power supply and harmonics and flicker with increasing applications in the distributed system. The main intent of this paper is to design an MC-UPQC to solve the power quality issues in the distribution system. The MC-UPQC involves two series Voltage Source Converter (VSC), where the power is transferred from one feeder to another to eliminate the "voltage sag, swell, interruption, and transient response." The hybrid meta-heuristic algorithm Beetle Swarm-based Butterfly Optimization Algorithm (BS-BOA) is developed by the combination of Beetle Swarm Optimization (BSO) and Butterfly Optimization Algorithm (BOA). The proposed BS-BOA optimizes the membership limit by the hybrid meta-heuristic algorithm, from which the control rules are generated for inputs. The major benefit of the optimized FLC-based MC-UPQC is its quick behavior in minimizing the Total Harmonic Distortions (THD). The comparative analysis was done over the traditional controllers to validate their effectiveness. From the analysis, the THD of the proposed BS-BOA-FLC-MC-UPQC is 99.99% better than BOA-FLC-MC-UPQC and 80% better than BS-FLC-MC-UPQC. Thus, the simulation result has outperformed the proposed method and has attained improved power quality.
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Optimal Operation of Multi-Converter-UPQC for Power Quality Improvement in Distribution System using Optimized Fuzzy Logic Controller

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Keywords: Multi-converter-UPQC; Distribution System; Power Quality Improvement; Optimized Fuzzy Controller; Voltage Source Converter; Beetle Swarm-based Butterfly Optimization Algorithm

Nomenclature

Abbreviation	**Description**
BOA	Butterfly Optimization Algorithm
MC-UPQC	"Multi converter-Unified power quality conditioner"
BSO	Beetle Swarm Optimisation
APF	Active Power Filters
ANN	Artificial Neural Network
THD	Total Harmonic Distortion
VSC	Voltage Source Converter
FLC	Fuzzy Logic Controller
UPFC	Unified Power-Flow Controller
BS-BOA	Beetle Swarm-based Butterfly Optimization Algorithm
PLL	Phase-Locked Loop
DCC	Diode Clamped Converter
UPQC	Unified Power-Quality Conditioner
MLI	Multi-Level Inverters
SRF	Synchronous Reference Frame
IPFC	Interline Power-Flow Controller
3P4W	Three Phase Four-Wire
DEO	Differential Evolution Optimization
MG	Micro Grids
PCC	Point of Common Coupling

1. Introduction

The revolution occurring in electronic technologies has crowded the "electrical system with non-linear loads." Handling the basic levels of power quality is a very complex task. Some basic power quality levels are the current of constant magnitude and sinusoidal voltage at changing load conditions (Khadkikar and Chandra 2011; Kinhal et al. 2011). These issues can be resolved by the passive filters, but their size leads to resonance and amplification in harmonic currents, so there is a need to find other solutions (Mohammadi et al. 2009). These problems are handled by the APF that is compressed in size, and it does not lead to cause amplifying or resonance harmonic currents. The voltage-linked issues in the power quality are compensated by the series APF and the present linked issues in the power quality is suppressed by the shunt APF (Rezaeipour and Kazemi 2008; Devaraju et al. 2012; Rao and Subhransu 2010).

At the level of distribution, the UPFC extension is the UPQC. In a supply feeder, the current, as well as the voltage imperfections, are simultaneously compensated by the combination of shunt and series converters (Jindal et al., 2007; Ansari et al., 2015). The most recently introduced "multi-converter FACTS" devices are the generalized UPFC and the IPFC. Other than controlling the single line's power flow like UPFC, these devices handle the power flow of subnetwork or multiline. UPQC is connected via a dc-link capacitor, and it is an end-to-end shunt connection as well as series APFs. It resolves the current and voltage-linked power quality problems (Fujita and Akagi 1998; Monteiro et al. 2014). MLI provides several benefits like low DV/DT, less distortion, and low switching losses. The performance is enhanced by the higher level of the converter. DCC finds its use in utility power system applications, but it has the drawback of capacitor voltage unbalance (Chennai and Benchouia 2014). Capacitor voltage balance is performed by a proper switching control strategy or extra hardware. The cost and size are also improved for the entire system.

Every phase of the power quality theory can be handled, but it shows a limitation of polluted supply. This limitation can be handled by PQ theory having a harmonic extraction method and SRF-oriented control scheme (Teke et al. 2011; Massoud et al. 2010). The sequential instruction process is followed by the control schemes, devices, and still machines, and it does not make decisions or learn from the experiences (Barros and Silva 2010). The performance can be enhanced when the system follows these procedures. The best solution to handle all these is the MC-UPQC. An MC-UPQC is joined end-to-end by a dc link with three VSCs. Here, the voltage and current imperfections are balanced in one feeder, and voltage imperfections are balanced in the next feeder (Singh et al. 2007). The power transfer is provided among two nearby feeders for interruption and swell/sag compensation. Adding more series VSCs (Karanki et al. 2013; Khadkikar 2012) can extend this theory to multibus/multi-feeder systems. The system balances the interruptions without requiring storage capacity limitations and a battery storage system.

In the MC-UPQC, the voltage may occur between the different levels, and the capacity expansion is too difficult. Power quality improvement cannot be used in multilevel operations. Hence, the improved power quality is carried out by the optimized fuzzy controller. Consequently, it gives superior performance concerning the rising and settling time. They are very cheaper to develop. Some of the challenges of the existing methods are shown below. The unbalanced voltage and non-linear harmonic load are the power quality problems facing the challenges. Here, the voltage sags and swells are considered complex problems in power filters due to the shunt and series connection. Additionally, the unbalanced power supply in the feeder system leads to cause a series of problem and also reduce the power quality. The lack of quality of power is occurring in the system. Here, the power supply in the battery is high in larger distributed systems. To overcome these challenges, a new design of MC-UPQC is to solve the power quality issues. The optimized FLC is employed to make the faster transient response to reduce the THD on the load and source-side "voltages and currents" on both feeders.

The contribution of the paper is enlisted in the below manner:

- To model an optimally controlled MC-UPQC for solving the issues in the power quality based on the FLC theory in the distribution system. It is solved based on SRF theory. Here, the FLC helps to reduce the THD of the current sources. Moreover, the FLC helps to achieve better performance in terms of quick response and nominal cost, and also it attains high reliability in the MC-UPQC system.
- To adopt a new control strategies for MC-UPQC based on optimized FLC via the development of a hybrid meta-heuristic algorithm by merging two algorithms like BSO and BOA called BS-BOA that optimizes the membership limit of FLC, from which the control rules are generated for different input signals. BS-BOA helps to resolve optimization problems with a minimum time. Consequently, it also attains a very faster transient response in the MC-UPQC. It offers good quality power by providing constant voltage.
- To propose an optimized FLC-based MC-UPQC for achieving high voltage and current and designed in various ways for reducing the cost along with the BS-BOA-optimization helps in maximizing the convergence rate. It compensates for the current and voltage in two feeders, where the fuzzy logic controller will be very fast. Consequently, the MC-UPQC system is utilized for efficacy solutions for voltage and harmonics. Here, the MC-UPQC helps to sustain the load end voltage on the supply side. Additionally, it helps to improve the voltage quality in distributed systems.
- The optimized FLC-based MC-UPQC is utilized for quick behavior in minimizing the Total Harmonic Distortions (THD) on the load side voltages and currents on both feeders. It helps to reduce the THD in feeder 1 and feeder 2. The analysis of the developed controller-based MC-UPQC over the conventional controllers for validating its effectiveness.

The upcoming part of the remaining sections is depicted here: Section I offers the MC-UPQC in the power quality improvement for the distribution system. The various works related to the MC-UPQC are listed in Section II. The improved power quality in MC-UPQC is described in Section III. Section IV shows the MC-

UPQC-based optimized fuzzy controller is described. The "results and discussions" are evaluated in Section V. Section VI provides the conclusion.

2. Literature Survey

In (Vinnakoti and Kota 2018a) have introduced a five-level DCC-oriented UPQC and by ANN-oriented controller. The performance was investigated on a harmonic supply voltage and non-linear unbalanced loads. Additionally, voltage-related issues like swell and sag were also taken into account. The ANN was trained using "Levenberg-Marquardt" backpropagation algorithm. It has maintained the required "dc-link capacitor voltage" and was used for the efficient generation of reference signals. The experiment was performed in Matlab/Simulink software having UPQC and two-level UPQC with the help of ANN control and SRF-oriented control schemes. Better performance was retrieved, and the dc-link capacitor voltage's response was discussed. The enhancement of the presented controller was revealed by comparing the %THD in supply current and load voltage.

In (Rajani and Raju 2013) have proposed a new method for a 3P4W distribution system using MC-UPQC. The 3P4W framework was identified from a "three-phase three-wire system." The series part MC-UPQC has used the neutral of the series transformer. A novel control scheme was also proposed to compensate for the unbalanced load currents. In the shunt part, the neutral current was balanced with the help of the inverter topology. In all the operating conditions, the neutral transformer series has attained the virtual zero potential. The superiority of the presented MC-UPQC-oriented 3P4W distribution system was revealed by the experimental outcomes on MATLAB/SIMULINK.

In (Senthilnathan and Annapoorani 2016) have proposed power quality improvements of the 3-feeder system based on voltage source converters utilizing the MC-UPQC. The control strategy depended on the ANN using the "Levenberg–Marquardt back-propagation algorithm" for handling the system voltage profile and lessening the unbalance swells and sags in the system. The hysteresis loop revealed the pulse generation by differentiating the error signals, and the superiority was verified utilizing MATLAB/SIMULINK.

In (Paduchuri et al. 2014) have enhanced the power quality issues using a model of MC-UPQC. This model incorporated the FLC technique and modified SRF theory. The current and the voltage were balanced in the two feeders by connecting the newly designed controller to a source. The extension of UPQC was the MC-UPQC. This system was connected by one shunt VSC and two series VSC. The voltage swell, transient response, sag, and interruption were lessened by conveying the power from one feeder to another. The control schemes of MC-UPQC were modeled based on FLC and advanced SRF theory. In the case of the dc-link voltage controller, the FLC's transient response was very speedy. The enhancement of the developed system was shown using MATLAB/Simulink software.

In (Vinnakoti and Kota 2018b) have labeled an efficient ANN controller for UPQC was revealed for efficient control and operation. The complexity and cost were minimized by the ANN controller. The controller performance was investigated under-voltage swell and sag, load unbalances, and supply voltage and load current harmonics. The outcomes demonstrated the improvement of the ANN controller.

In (Koroglu et al. 2016) have addressed interline custom power devices for medium voltage level (11 kV) known as MCUPQC. It was developed for several power quality disturbances. The power quality disturbances were extracted and detected by an improved phase- locked loop- oriented control technique. The series compensators of MCUPQC have lessened the unbalanced voltage sags, having interruption, swell, and phase jumps. The effect of phase angle jumps was lessened by the presage compensation method composed of a new phase- freezing algorithm. The shunt compensator of MCUPQC was examined for "direct current link voltage regulation, reactive power compensation, and harmonic compensation." The outcomes displayed that the MCUPQC could balance the voltage and power imperfections using PSCAD/EMTDC.

In (Kumar et al. 2018) have enhanced the power quality by modeling an MC-UPQC. The framework could be adjusted for current load defects and supply voltage on principle feeder. The fault occurred on alternate feeders by the full payment of supply voltage. All the converters provided a typical dc-interface capacitor and were linked on the dc side by giving one DC connect capacitor. The major issue in the MC-UPQC gadget was the high releasing time of the DC connect capacitor. This issue was resolved by a progressed ANN-oriented MC-UPQC. The transient reaction was fair for the PI dc-connect voltage controller. Hence, in light of the vitality of a dc-interface capacitor, a fast-acting "dc-connect voltage controller" was developed. Compared to the dc-connect voltage controller, the transient reaction was very speedy for this controller. The transient reaction was improved by employing the fluffy rationale controller. The power quality of the framework was developed by expanding the DC capacitor charging yield voltage, which revealed the superiority of the proposed method.

In (Babu et al. 2015) have improved the power quality issues by modeling a fuzzy logic controller-oriented MC-UPQC. The current and the voltage were balanced in the two feeders by connecting the novel-modeled controller to a source. The voltage swell, transient response, voltage sag, and interruption were lessened by conveying the power from one feeder to another. Based on the MSRF theory having FLC, the control strategies of MC-UPQC were modeled. In the context of the dc-link voltage controller, the FLC's transient response was very quick. The compensation performance and relevant simulation analysis were examined for the MC-UPQC and the FLC.

In (Rao et al. 2021) have proposed a new control technique for the unified power quality improvement for harmonic distribution using PSO-Fuzzy logic. The control algorithm was developed on a unified power quality conditioner.

Alsammak and Mohammed, (2021) have improved the power quality with the fuzzy logic controller (FLC) based on UPFC, which can control both active and reactive power flow and enhance transient stability. The theoretical analysis has been proved by implementing the system in MATLAB/SIMULINK package. The stability was increased, and optimum power flow was obtained, then the "optimum value of DC capacitor of 2.5 mF has been selected between the two converters".

In (Alshehri et al. 2019) have developed a new online intelligent BESS-based controller that has helped to enhance the quality of the power of the MG system. Also, it was targeted at the steady state condition.

Jin *et al.* (2020) have designed an effective control strategy for UPQC in the dq0 detection model. Here, the "Space Vector Pulse Width Modulation (SVPWM)" was developed for detecting the harmonic power supply. **Eltamaly *et al.* (2020)** have developed a Maximum Power Point Tracking (MPPT) technique to track the power in PV rays. Here, "Particle Swarm Optimization (PSO)" was introduced to allocate the Power Quality Disturbances (PQDs) units in several operating conditions. **In (Liu *et al.* 2021)** have suggested that Time-Dependent Spectral Features (TDSFs) detect the power quality. The "Improved Complete Ensemble Empirical Mode Decomposition with Adaptive Noise (ICEEMDAN)" was developed to decompose the intrinsic mode. **In (Li *et al.* 2021)** have investigated the False Data Injection Attack (FDIA) to prevent various activities in cyber attacks. Here, the secured Anomaly Detection Model (ADM) was developed to prevent attacks in the network. **In our research,** the author has adopted the control schemes of MC-UPQC based on optimized FLC via the development of a new method called BS-BOA. The major scope of this work has designed the latest MC-UPQC to solve the power quality issues.

Although there exist several features in MC-UPQC, it leads to the MC-UPQC improving the power quality. Some of the major features and challenges are listed in Table 1. ANN (Vinnakoti and Kota 2018a) reduces the harmonics in supply currents and load voltage, and it also expiates voltage swell and voltage sag efficiently. But, it has very low efficiency close to the nominal operating point. Neuro-Fuzzy controller (Rajani and Raju 2013) expands the conventional 3P3W system to a 3P4W system, and it also balances the reference source current beneath unbalanced load conditions. Still, the installation of UPQC to adjust the various power quality conflicts does not play a significant role. ANN (Senthilnathan and Annapoorani 2016) has the capability of expiating the swell and sag, and it also reduces the power quality problems in the 3-feeder system. Yet, it produces large and bulk dc inductors with huge dc-link losses. Modified SRF theory and FLC technique (Paduchuri et al. 2014) perform better reactive power compensation and acquire a quick transient response. But, it cannot be utilized in multi-level operations. ANN (Vinnakoti and Kota 2018b) generates the reference currents for the shunt converter and reference voltages for the series converter, and it also enhances the system power factor. Still, the conduction loss acquired is very large. The phase-locked loop-based control technique (Koroglu et al. 2016) withdraws and distinguishes the power quality disturbances in a multi-feeder system. It also generates an active power flow of MCUPQC. Yet, voltage unbalance happens at distinct levels. ANN (Kumar et al. 2018) is dependent on recognizing the line currents only, and it also enhances the power quality of the framework. But, it requires central control to work well. FLC (Babu et al. 2015) obtains a quick transient response, and it also expiates the distorted non-linear load current. Still, it needs a large count of switching devices to improve its capacity. PSO-fuzzy logic (Rao et al. 2021) is easy to implement. It isn't easy to define the initial design parameters. FLC (Alsammak and Mohammed, 2021) is very cheaper to develop. It requires a larger magnitude to control the system. ANN (Alshehri et al. 2019) is very easier to use. It has large complexity of network structure. These challenges can be considered a future motivation for implementing an efficient novel model of MC-UPQC.

Table 1. Features and Challenges of state-of-the-art Multiconverter-UPQC methods

Author [citation]	**Methodology**	**Features**	**Challenges**
(Vinnakoti and Kota 2018a)	ANN	• It helps to minimize the harmonics in supply currents and also the load voltage. • It expiates voltage swell and voltage sag efficiently.	• It has very low efficiency close to the nominal operating point.
(Rajani and Raju 2013)	Neuro-Fuzzy controller	• It expands the conventional 3P3W system to the 3P4W system. • It balances the reference source	• The installation of UPQC to adjust the various power quality conflicts does not play a significant role.

		current beneath unbalanced load conditions.	
(Senthilnathan and Annapoorani 2016)	ANN	• It has the capability of expiating the swell and sag. • The 3-feeder system it utilizes decreases the power quality.	• It produces large and bulk dc inductors with huge dc-link losses.
(Paduchuri et al. 2014)	Modified SRF theory and FLC technique	• It performs better reactive power compensation. • It acquires quick transient responses.	• It cannot be utilized in the multi-level operation.
(Vinnakoti and Kota 2018b)	ANN	• It generates the reference currents for the shunt converter and reference voltages for the series converter. • It enhances the system power factor.	• The conduction loss acquired is very large.
(Koroglu et al. 2016)	Phase-locked loop-based control technique	• It withdraws and distinguishes the power quality disturbances in the multi-feeder system. • It generates an active power flow of MCUPQC.	• Voltage unbalance happens at distinct levels.
(Kumar et al. 2018)	ANN	• It is dependent on recognizing the line currents only. • It enhances the power quality of the framework.	• It requires central control to work well.
(Babu et al. 2015)	FLC	• It obtains a quick transient response. • It expiates the distorted non-linear load current.	• It needs a large count of switching devices to improve its capacity.
(Rao et al. 2021)	PSO-fuzzy logic	• It is easy to implement.	• It isn't easy to define the initial design parameters.
(Alsammak and Mohammed, 2021)	FLC	• It is very cheaper to develop.	• It requires a larger magnitude to control the system.
(Alshehri et al. 2019)	ANN	• It is very easier to use.	• It has large complexity of network structure.

3. Improved Power quality in MC-UPQC

3.1 Line Diagram of MC-UPQC

In the source, the reactive current is available from the feeder voltages. MC-UPQC can achieve high current and voltage (Rajkumar et al. 2022). It has the capability for injecting power (Jose et al. 2015) (Jose et al. 2013) to the sensitive loads by using the DG at the time of source voltage interruption. The diagrammatic representation of the developed MC-UPQC is displayed in Fig. 1.

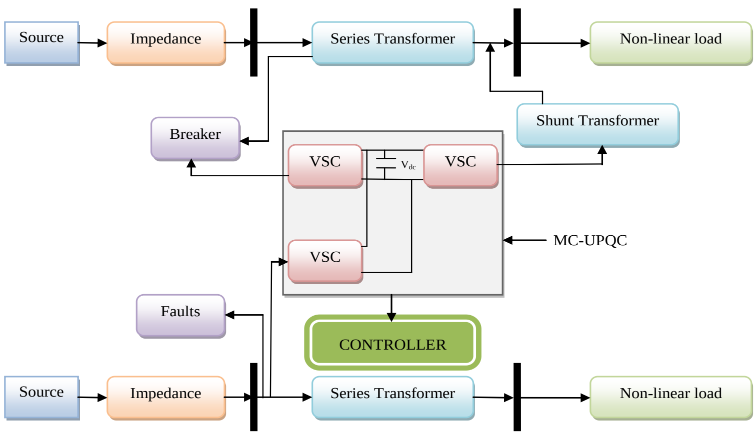


Figure 1. Single-line diagrammatic representation of MC-UPQC

The MC-UPQC contains one shunt voltage and two series voltage converters that are joined in a common capacitor of DC-link. This helps to control it independently for balancing power quality problems. In feeder 1, it is damaged by harmonic distortions, unbalanced currents/voltage in the load sides, and the source of both feeders. The load in feeder two represents a linear load, and therefore it does not contain any unbalanced power supply, interruption, swell, sag, and harmonic distortion. Therefore, no impact occurs in both of these feeders. Among the two feeders, the two series VSCs are joined in the series via a series transformer. On the load side, the shunt VSC is joined to feeder 1 via a shunt transformer. Hence, the switching harmonics are avoided in the MC-UPQC by joining the power filter and having a commutation reactor L with the entire VSCs. This is achieved by investigating one possible scheme for MC-UPQC.

3.2 Control Strategy of MC-UPQC

The strategy is the significant role of MC-UPQC. It can apply any electronic device to maintain the power supply. Consequently, the control strategy is utilized to detect the behavior and current operations of the particular distribution system. Moreover, the MC-UPQC depends on control techniques to enhance the system's (Vinotha et al. 2019) (Jose et al. 2014) power quality. Here, the performance of the MC-UPQC is achieved based on reference signals either from voltages or current signals. The developed control scheme produces the received signals from the series and shunts the "voltage source converter of the MC-UPQC." The control method extracts harmonic and reactive components, voltage and the current unbalance, harmonics and swell, voltage sags, source voltage distortions, and load currents of both feeders. The circuit topology of MC-UPQC is depicted in Fig. 2.

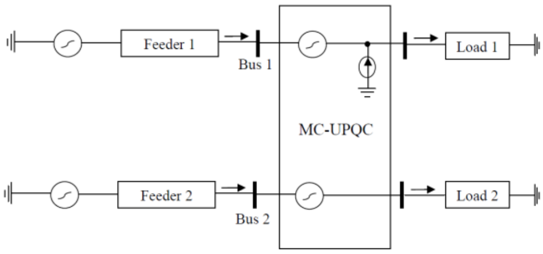


Figure 2. The circuit topology of MC-UPQC

3.3 Control Strategy of Shunt VSC

The control algorithm related to "the shunt VSC block" is described below. Here, the shunt VSC is modeled with the help of the FLC technique and MSRF theory. It offers better regulation of the familiar DC-link capacitor voltage, feeder one load current's reactive components, and balancing of harmonics than the traditional techniques. In the case of distortion in the supply voltage, synchronization is attained by a PLL using the voltage supply. The sensing of the voltage takes place, and it is subjected to the PLL for producing two quadrature unit vectors, such as cosine and sine outputs from the PLL for calculating the 120^0 phase displacement in every phase. Based on the unit vector template, the shunt VSC depends on the MSRF theory technique. The phase angle of every current and phase voltage is extracted in a three-independent two-phase system represented in the form of lag $\Pi/2$. It contains the three-phase unbalanced and balanced of every "phase system independently." The load synchronous reference currents are attained by transforming the three-phase load currents for the feeder one, as in Eq. (1) and Eq. (2).

$$\begin{bmatrix} i_{m-d} \\ i_{m-q} \\ i_{m-0} \end{bmatrix} = \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} \begin{bmatrix} i_{m-a} \\ i_{m-b} \\ i_{m-c} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin \omega z & \sin\left(\omega z - \frac{2\pi}{3}\right) & \sin\left(\omega z + \frac{2\pi}{3}\right) \\ \cos \omega z & \cos\left(\omega z - \frac{2\pi}{3}\right) & \cos\left(\omega z + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2}$$

The second-order low pass filter transfers the primary "direct axis component current into DC quantities." It is then included in the optimized fuzzy logic output for producing novel "reference shunt feeder currents" as in Eq. (3) and Eq. (4).

$$i_{x-d}^{rfe} = \bar{i}_{qd} + \Delta I_{dc} \tag{3}$$

$$i_{x-q}^{rfe} = i_{m-q} \tag{4}$$

In the DC-link capacitor, the consumed power is achieved via the switching losses, and the series inverter reduces the DC bus voltage's average value. The remaining distortions, such as sudden change and unstable conditions, lead to DC bus voltage oscillations. It is subjected to the optimized FLC to minimize the error between the measured and the desired capacitor voltage. The output controlling signal is given to the current control system of shunt VSC. The power is received from the source for stabilizing the DC capacitor voltage by the shunt VSC. The feeder current's quadrature components are applied to zero, and the feeder current's direct component is applied to load direct components. Thus, there exists no reactive component and the harmonic current in feeder 1. The novel reference shunt feeder currents present in Eq. (3) and Eq. (4) are converted to the abc reference currents as in Eq. (5).

$$\begin{bmatrix} i_{x-a}^{rfe} \\ i_{x-b}^{rfe} \\ i_{x-c}^{rfe} \end{bmatrix} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \begin{bmatrix} i_{x-d}^{rfe} \\ i_{x-q}^{rfe} \\ i_{x-0}^{rfe} \end{bmatrix} \tag{5}$$

The reference current abc is included in the shunt currents. Hence, the currents are controlled by sensing the reference frame currents by the relay. The shunt VSC's compensation currents are subjected to the controller part directly, as in Fig. 3.

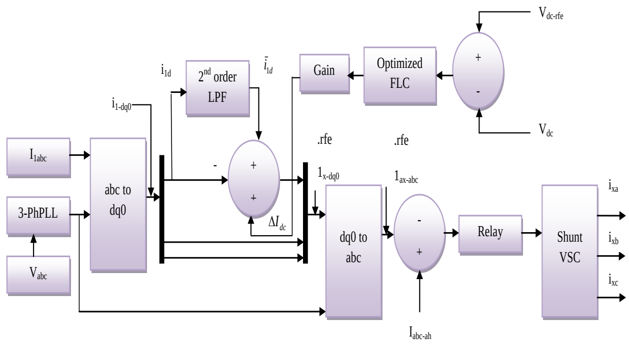


Figure 3. The SRF-oriented control scheme of the shunt VSC

3.4 Control Strategy of Series VSC

The series VSC block using the control strategy is displayed in Fig. 3. It is developed with the help of the MSRF theory, along with the enhancement of the PWM generator. When differentiated from the existing techniques, the developed series VSCs provide superior compensation for interruptions in both feeders. Based on the unit vector template, the series VSC block is functioned using the novel MSRF theory. The PLL senses the distorted three-phase supply voltages for producing two quadrate unit vectors. The transformation of "three-phase load voltages into load synchronous reference voltages" takes place as in Eq. (6) and Eq. (7).

$$\begin{bmatrix} v_{m-d} \\ v_{m-q} \\ v_{m-0} \end{bmatrix} = \begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} \begin{bmatrix} v_{m-a} \\ v_{m-b} \\ v_{m-c} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin \omega z & \sin\left(\omega z - \frac{2\pi}{3}\right) & \sin\left(\omega z + \frac{2\pi}{3}\right) \\ \cos \omega z & \cos\left(\omega z - \frac{2\pi}{3}\right) & \cos\left(\omega z + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{7}$$

While considering the series control aim, if the supply voltage is considered, the load voltage must be maintained sinusoidal with a constant amplitude. Hence, the subtraction of the predicted load synchronous reference $dq0$ voltages V_{m-dq0} takes place as in Eq. (8). The transformation of the "compensation reference feeder $dq0$ voltages to the synchronous reference feeder voltages" takes place as in Eq. (9).

$$\begin{bmatrix} v_{x-d}^{rfe} \\ v_{x-q}^{rfe} \\ v_{x-0}^{rfe} \end{bmatrix} = \begin{bmatrix} v_{m-d} \\ v_{m-q} \\ v_{m-0} \end{bmatrix} \begin{bmatrix} v_{x-d}^{ex} \\ v_{x-q}^{ex} \\ v_{x-0}^{ex} \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} v_{ax-a}^{rfe} \\ v_{ax-b}^{rfe} \\ v_{ax-c}^{rfe} \end{bmatrix} = \begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix}^{-1} \begin{bmatrix} v_{x-d}^{rfe} \\ v_{x-q}^{rfe} \\ v_{x-0}^{rfe} \end{bmatrix} \tag{9}$$

The forwarding of the “compensation synchronous reference *abc* voltages” to the developed PWM generator occurs. The “PWM generator compensation voltage’s” output is provided as input directly to the control portion of the series VSC as in Fig. 4.

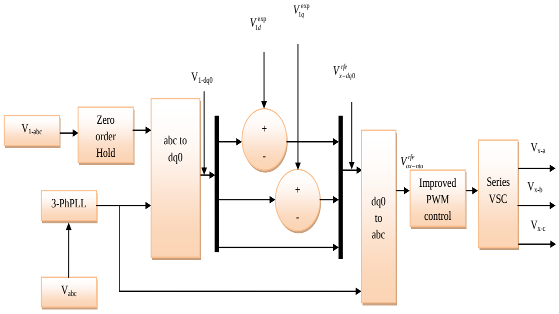


Figure 4. The SRF-oriented control scheme of the series VSC

4. Optimized fuzzy controller-based MC-UPQC

4.1 Designed Model

The main idea of the proposed method is to model an MC-UPQC for handling power quality issues. The SRF theory is adopted by this advanced method. In general, the MC-UPQC is composed to transfer the power from one feeder to another and eradicates the transient response, interruption, swell, and voltage sag of the system. This technique uses the control schemes of MC-UPQC based on an optimized Fuzzy theory called FLC in SRF. The optimized fuzzy theory is done using BS-BOA as a contribution, and the effective improvement of FLC is accomplished by the proposed hybrid BS-BOA. The “error DC capacitor voltage (V_{dc}) and reference DC capacitor voltage error” (ΔV_{dc}) are given as optimized FLC for controlling the signal in MC-UPQC for optimal power quality improvement. The SRF theory with optimized FLC helps to perform the effective control strategy of MC-UPQC. The reference signal is estimated based on the SRF theory. In a real-time system, the active power filter is controlled by the generic voltages. In FLC, the membership limits of the triangular membership function are optimized by the proposed BS-BOA. The major benefit of this optimized fuzzy controller-oriented MC-UPQC is its quick behavior in minimizing the THD on the load and “source-side voltages as well as currents on both the feeders.” The proposed architecture of MC-UPQC is shown in Fig. 5.

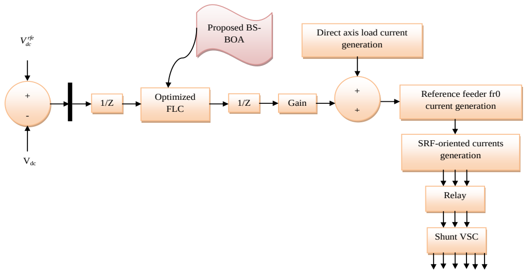


Figure 5. Architectural representation of MC-UPQC using optimized fuzzy controller

4.2 Fuzzy Logic Controller

FLC (Rajani and Raju 2013) (Paduchuri et al. 2014) helps to design a system with MC-UPQC under a distribution system based on fuzzy theory. The input value is a logical variable that takes continuous values between 0 and 1. The linguistic schemes are used in the automatic control model using expert knowledge based on fuzzy logic theory. FLC was first developed in 1965 at California University by Professor Lotfia Zadeh. It is a technique to process inaccurate data. Its applications were not revealed until the availability of powerful controllers and computers. Here, the fuzzy rule depends on the control operation that is produced utilizing the fuzzy set theory. The fuzzy controller plays the main role in compensating for the power quality problem (Roy et al. 2022) (Rajkumar et al. 2017). There are several steps in the fuzzy controller, such as decision-making, defuzzification, and fuzzification. During the fuzzification process, the crisp value is varied from the fuzzy value. It does not contain a fixed procedure set, and it is attained by distinct fuzzifier types. There exist several fuzzy set shapes like trapezoidal, triangular, and more. The output of the fuzzified process is generated by the concerned inputs via creating a set of rules. The input to the FLC is the change of error and the voltage error. Fuzzy sets are described for every input as well as the output variable. The membership functions, in the case of both the input and output variables, seem to be triangular. Here, the fuzzy technique represents the center of the area. Fig. 6 displays the block diagram representation of BS-BOA-FLC generating the controlled signal in MC-UPQC.

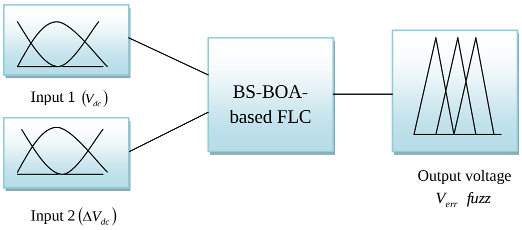


Figure 6. Generating controlled signal in MC-UPQC based on BS-BOA-FLC

The output from the database produces the relation of inference BR as in Eq. (10). The output, as well as input variables of the data bus or the controlled system, is composed of a description of a fuzzy set. The memberships of fuzzy are modeled based on Eq. (10).

$$BR^{(PN)} = IF\ U_1\ is\ FG_1\ AND\ U_2\ is\ FG_2 \cdots U_{nh}\ is\ FG_{nh} \\ then\ V\ is\ CR^{(PN)} \tag{10}$$

Here, the term $PN = 1,2,3 \cdots NH$, which NH represents the count of rules, the fuzzy sets are described by $FG_1, FG_2, \cdots FG_{nh}$, the count of fuzzy variables are denoted by nh , the control or the output variable is defined V . The term $U_1, U_2, \cdots U_{nh}$ defines the input variables vector. Using the provided rule base, the fuzzy controller calculates the particular input signals for describing the control action. The FLC is designed by inferring the "plant control from the two input state variables," such as variation in reference "DC capacitor voltage error (ΔV_{dc}) and error DC capacitor voltage" (V_{dc}) as in Eq. (11).

$$v_{err}\ fuzz = v_{dc} - v_{dc}^{rfe} \tag{11}$$

The fuzzy rules are modeled for the control input for V_{dc} and ΔV_{dc} . It requires only a less quantity of real loss for regulating the voltage that is considered as the FLC's output. The fuzzy logic output is taken then, and then it is forwarded to the feeder current $dq0$. The MSRF-oriented currents are subjected to the relay directly, and a control signal is sensed to shunt the VSC control circuit.

4.3 Hybrid Beetle Swarm with Butterfly Optimization Algorithm

The hybrid BS-BOA optimizes the membership limits of the FLC for minimizing the THD on the load and source-side "voltages and currents on both the feeders" of MC-UPQC. Compared to other algorithms, hybrid algorithms can provide better performance. It can also provide rapid discovery of better solutions. Here, the BSO and BOA are merged with a new method, BS-BOA, that can reduce the total harmonic distortions in the distribution system with a new controlled MC-UPQC. BOA (Arora and Singh 2018) describes the butterfly's food-foraging behavior. The optimization of the BOA search agents called butterflies. The fragrance having less intensity is produced by the butterfly. With its fitness, the intensity is correlated. The improvement in fitness is based on the movement of the butterfly. Other butterflies can sense the fragrance since it propagates over long distances and helps to share personal information. When a butterfly senses fragrance from the remaining butterflies, the movement is called the global search.

Here, the fragrance is taken from the scent and personal touch. Here, the sensing and processing of the BOA depend on the three stipulations such as power exponent (b), stimulus intensity (J), and modality of the sensory (d). The sensory measures the energy form, and it processes it in identical ways. Modality means the raw input that is being employed by the sensors. Here, the term J has defined the magnitude of the actual stimulus, and also it is linked with the fitness solution. Moreover, it emits a large quantity of fragrance, and the remaining butterflies in the surrounding sense and attract to it. Power is referred to as the exponent with whom the intensity arises. The term b permits "response compression, linear response, and regular expression." It evaluates the response when J enhanced, and the fragrance (g) enhances faster J. Response compression is when J increases, g increases gradually when compared to J. When J enhanced, g it enhances in a proportional manner, known as a linear response. Hence, response compression is used to describe the magnitude of J.

Based on two significant issues, the butterfly's natural phenomenon g and the variation J is taken. The variable J owes the objective function. Yet, g remains relative, and so, it can be sensed by the remaining butterflies. Various modalities d are utilized to compare the smell. When the butterfly with little J takes the movement towards the butterfly with large J, g it tends to increase faster than J. Hence, with a degree of absorption, g it is permitted to change, and it can be fulfilled using the power exponent parameter b. The fragrance is described as the stimulus intensity of the physical as in Eq. (12).

$$g = dJ^b \tag{12}$$

Here, the "sensory modality is denoted by d, the power exponent based on modality is denoted" by b, the fragrance magnitude is denoted by g, and the stimulus intensity is denoted by J. The limits of b and d lie in the range of 0 to 1. The variation of absorption is characterized by the parameter b. The value $b=1$ denotes the absence of the absorption of fragrance. This means that the fragrance propagation takes place in an idealized environment. Hence, in the domain, the fragrance is sensed by the butterfly from anywhere. So, the global optimum is attained easily. The value $b=1$ indicates that the fragrance cannot be sensed by the remaining butterflies. Therefore, the behavior of the algorithm is controlled by the parameter b. The parameter d describes the behavior of the BOA and the speed of convergence. In the theoretical format, the value lies as $d \in [0,\infty]$, but in the practical format, it is described by the system characteristics to be optimized. The "convergence speed of the algorithm" is affected by the values of d and b. The "intensity is proportional to the objective function" in most maximization issues.

The characteristics of butterflies concerning the search algorithm can be described in the following ways:

- The butterflies emit a fragrance that helps in attracting each other.
- The stimulus intensity of the objective function is determined.
- All the butterflies perform random movements, which help to emit more fragrance.

The BOA contains three stages "initialization, iteration, and the final phases." In the first phase, the initial step is executed. Next, it iteratively performs the search. When the optimal solution is reached, the algorithm terminates in the final step. In the initialization phase, it describes the objective function together with its solution space. The values of the parameter are also assigned. Next, an initial population is created for optimization purposes. Since the total butterflies count remains constant. Moreover, the information is stored in fixed memory. The butterfly's position is generated randomly. The fitness values are stored and calculated. Once the initialization phase is completed, the iteration phase starts, in which the searching is performed with the artificial butterflies.

The second phase describes the iteration count. It achieves to perform the movement towards new positions in every iteration, and next, the evaluation of fitness values takes place. At various positions, the fitness values are computed for all the search spaces. Using Eq. (12), the butterflies produce fragrance at their positions. The two main phases are "the local search phase and the global search phase." Eq. (13) describes the search phase in which the butterfly performs the movement of the butterfly h^*.

$$y_j^{l+1} = y_j^l + \left(ra^2 \times h^* - y_j^l\right) \times g_j \tag{13}$$

In the above equation, the optimal solution found between all the iterations is denoted by h^* a random number of interval ranges between 0 and 1 and is depicted by ra the "solution vector y_j for j^{th} butterfly in iteration count l is denoted" by y_j^l, and g_j denotes the j^{th} butterfly fragrance. Eq. (3) describes the local search phase as in Eq. (14).

$$y_j^{l+1} = y_j^l + \left(ra^2 \times y_k^l - y_j^l\right) \times g_j \tag{14}$$

Here, y_j^l and y_k^l represents j^{th} and k^{th} solution space for the butterflies. The BOA has various advantages it is simple, can handle real-world optimization problems, and is very effective than various meta-heuristic algorithms. But, it suffers from shortcomings, like being less efficient in handling combinatorial problems, poor self-adaptive techniques, etc. Hence, to overcome these drawbacks, BSO is combined with the proposed method BS-BOA. In this paper, the designed BS-BOA technique provides better performance. It can solve the optimization problem in less time. BSO (Chen et al. 2018) integrates the concept of both PSO and BAS. The BSO can handle poor stability problems and overcome the problem of falling in a local optimum. Eq. (15) describes the present location update rules below.

$$y_j^{l+1} = y_j^l + w_j^{l+1} \tag{15}$$

Here, the position after the l^{th} iteration is represented by y_j^{l+1} and w_j^{l+1} is given by Eq. (16).

$$\begin{aligned} w_j^{l+1} &= w_j^{l+1} + d_1 \cdot ra \cdot \left(Qc_j^l - y_j^l\right) \\ &+ d_2 \cdot ra \cdot \left(Qh_j^l - y_j^l\right) + d_3 \cdot ra \cdot ur \end{aligned} \tag{16}$$

In the above equation, learning factors are defined by d_1, d_2, d_3 the present position to attain the optimal solution Qc_j^l, and the present global optimum is represented Qh_j^l respectively. The update rate produced by the BSO is represented by ur_j and is shown in Eq. (17).

$$ur_j = \delta^v \cdot c \cdot sign(g(y_{sv}) - g(y_{mv})) \tag{17}$$

Here hds, the right and left positions of every beetle are defined y_{sv}, and y_{mv} the fitness of every beetle's right and left position is represented by $g(y_{sv})$ and $g(y_{mv})$. The "pseudo-code" of the proposed BS-BOA is listed in Algorithm 1. The diagrammatic representation of the recommended BS-BOA is depicted in Fig. 7.

Algorithm 1: Designed BS-BOA

```
Begin
The initial population of nc butterflies y_j = (j = 1,2,···,nc) is generated
Determine the stimulus intensity J_j at y_j using g(y_j)
The switching probability sp, power exponent b, and sensor modality d are defined
while (l < l_max)
    For every butterfly buff present in the population, do
        The fragrance buff is computed by Eq. (12)
    end for
    The best buff is found
    For every butterfly buff present in the population, do
        A random number ra is generated from [0,1]
        if ra < sp then
            The movement takes place towards the best solution/butterfly by Eq. (13)
        else
            Present location update of BSO as in Eq. (15)
        end if
    end for
    The value b is updated
end while
The best solution attained is returned as output
```

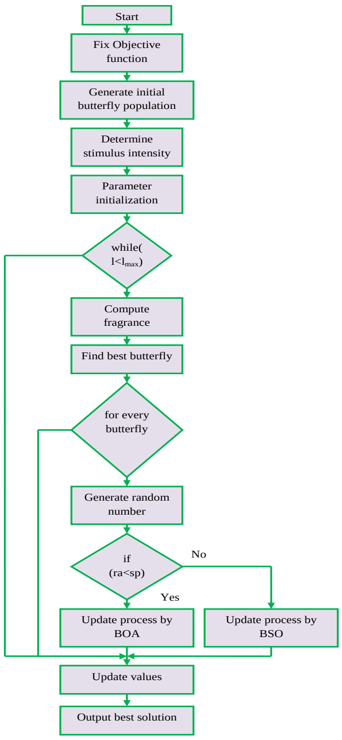


Figure 7. Flowchart of the proposed BS-BOA

4.4 Optimized Fuzzy Logic Controller

FLC is a flexible and intuitive knowledge-based system that is recently used for enhancing power quality. To further improvise the performance of the LLC, the tuning of the membership limit is introduced here, which is done by the proposed BS-BOA. The optimized FLC is employed for its transient response in the making MC-UPQC faster in minimizing the THD on the load and "source-side voltages as well as currents on both feeders." Here, five labels of optimized fuzzy subsets are used, such as PoLa-positive large, PoMe-positive medium, ZeRo-zero, NeMe-negative medium, and NeLa-negative large. A few of the effects of FLC optimization are depicted below. The FLC is used to speed up the response time in the distributed system. With the help of optimized FLC, it can synchronize the voltage to change the current in real time. It deals with the non-linearity and uncertainty variables in the actual controllers.

Table 2 displays the rules generated for voltage control. Here, the column and row denote the changes in error and error voltages, respectively.

Table 2. Rules generated for voltage control

		INPUT 2 [ΔV_{dc}]				
		NeLa	NeMe	ZeRo	PoMe	PoLa
INPUT 1 [V_{dc}]	NeLa	NeLa	NeLa	NeLa	NeSm	ZeRo
	NeMe	NeLa	NeLa	NeMe	ZeRo	PoSm
	ZeRo	NeLa	NeMe	ZeRo	PoMe	PoLa
	PoMe	NeSm	ZeRo	PoMe	PoLa	PoLa
	PoLa	ZeRo	PoSm	PoLa	PoLa	PoLa

Rather than the conventional FLC, the optimized FLC improves its performance by tuning the membership limits by the proposed BS-BOA. The solution encoding of membership limit optimization in FLC based on the entire rules is shown in Fig. 8. The bounding value of the membership limit lies in between the value of (-1, 1).

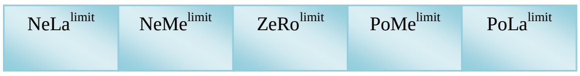


Figure 8. Solution encoding membership limit optimization in FLC

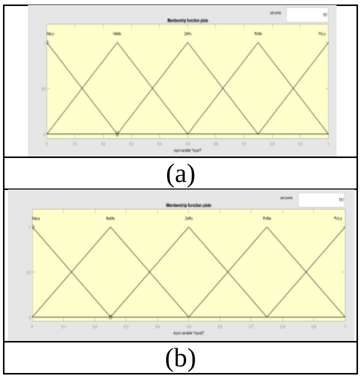
Here, the membership limits of each linguistic variable of fuzzy are considered as the parameters for optimization that has to be done by the proposed BS-BOA. The main scope of the designed BS-BOA-based MC-UPQC to enhance the power quality with the help of an optimized Fuzzy Controller is to reduce the THD. It is described mathematically as in Eq. (18).

$$Obj\ fun = \mathop{\arg\min}_{\{membership\ limits\}} \{THD\} \tag{18}$$

In the above equation, the "THD is described as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency." It is mathematically represented in Eq. (19).

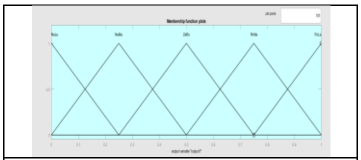
$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 \cdots}}{V_1} \tag{19}$$

Here, the term V_{nh} describes the RMS voltage of the nh^{th} harmonic. Fig. 9 displays the performance of the membership function regarding "error voltage, change of error voltage, and output voltage" generated by BS-BOA-based FLC.



(a)

(b)



(c)

Figure 9. Performance of membership function in terms of (i) Error voltage, (ii) Change of error voltage, and (iii) Output voltage

5. Results

5.1 Experimental setting

The designed BS-BOA-FLC-MC-UPQC was implemented in "MATLAB 2019a," and the experimental analysis was considered. Here, the power is transferred from feeder 1 to feeder 2 to eliminate the "voltage sag, swell, interruption, and transient response of the system." The proposed BS-BOA-FLC-MC-UPQC is differentiated with several conventional models such as general NN-MC-UPQC, MC-UPQC, FLC-MC-UPQC, and traditional heuristic-based FLC-MC-UPQC such as BS-FLC-MC-UPQC, and BOA-FLC-MC-UPQC to determine that the THD is minimized in the proposed BS-BOA-FLC-MC-UPQC. The parameter details for the proposed BS-BOA-FLC-MC-UPQC model are shown in Table 3.

Table 3. The parameter details of the designed BS-BOA-FLC-MC-UPQC model

S.no	Parameter	Value
1.	Number of the shunt voltage converter	1
2.	Number of the series voltage converter	2
3.	Name of Fuzzy membership function	Triangular
4.	Membership limit	(-1,1)
5.	Population size	10
6.	Maximum Iteration	25
7.	Frequency	50 Hz
8.	Voltage	400Vrms
9.	Shunt	15mH
10.	Two series transfer	1KVA
11.	DC-link capacitor	2200µF
12.	DC link voltage	700V
13.	Load	18mH

5.2 Simulation Model

The proposed BS-BOA-FLC-MC-UPQC model in the distribution system is depicted in Fig. 10.

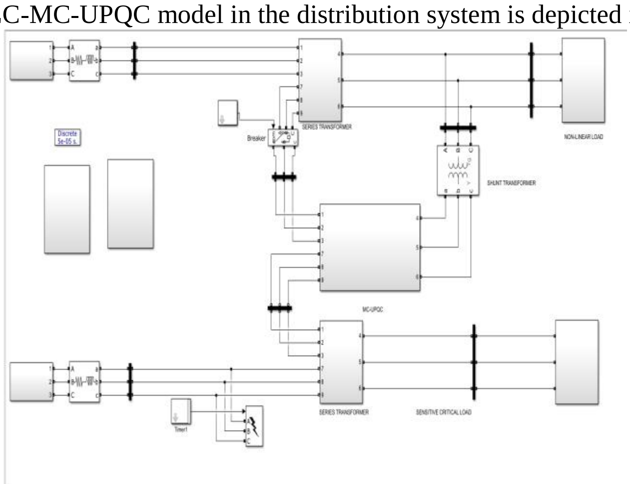
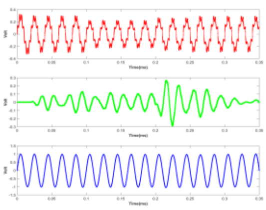


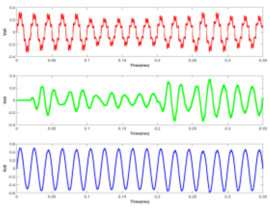
Figure 10. Proposed BS-BOA-FLC-MC-UPQC model in the distribution system

5.3 Performance analysis of MC-UPQC with feeder 1 and feeder 2

The performance of the designed BS-BOA-FLC-MC-UPQC over the conventional models connected with feeder 1 and feeder 2 is depicted in Fig. 11 and Fig. 12, respectively. The result shows the "bus 1 voltage, series compensation voltage, and load 1 voltage". The system is joined with two feeder systems for mitigating voltage sag swell and other disturbances. The source voltage is given with sag from 0.1sec to 0.2sec and swells from 0.2sec to 0.3sec. As per the concept, if the fault is occurring in feeders 1 and 2, there is an effect on the voltage across with other interruptions. To solve this problem, an optimal controlled BS-BOA-FLC is connected to the shunt VSC. It is clearly shown in the load voltage, which is solved effectively by the suggested BS-BOA-FLC compared to other controllers.



(a)



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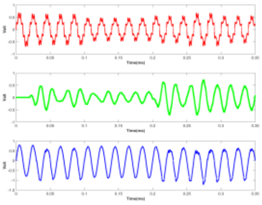

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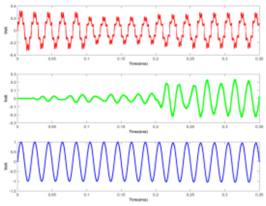
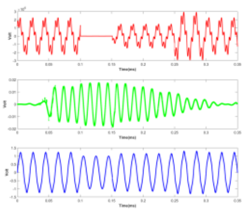
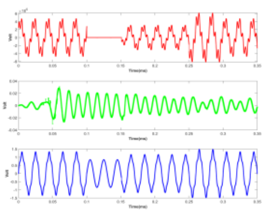


(d)

Figure 11. Performance of proposed MC-UPQC in terms of (a) General MC-UPQC system, (b) FLC-MC-UPQC, (c) NN-MC-UPQC and (d) BS-BOA-FLC-MC-UPQC for feeder 1.



(a)



(b)

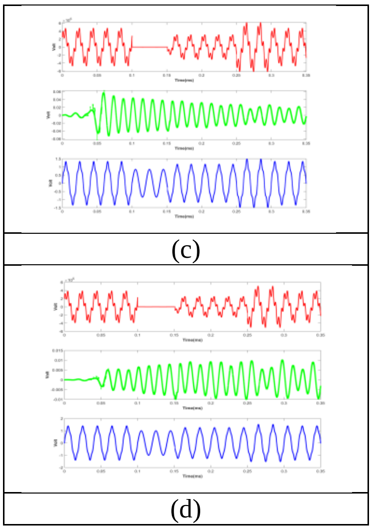


Figure 12. Performance of proposed MC-UPQC in terms of (a) General MC-UPQC system, (b) FLC-MC-UPQC, (c) NN-MC-UPQC and (d) BS-BOA-FLC-MC-UPQC for feeder 2

5.4 Performance evaluation of MC-UPQC connection with feeder 1and feeder 2 with different heuristic-based FLC

The performance analysis on BS-BOA-FLC-MC-UPQC over the conventional heuristic-based FLC-MC-UPQC is shown in Fig. 13 and Fig. 14 of feeder 1 and feeder 2, respectively. From the analysis, the designed BS-BOA-FLC-MC-UPQC model gets higher performance when compared with the other heuristic-based controllers. Finally, the maximum voltage rate in two feeders, is evaluated by varying the time vs. voltage.

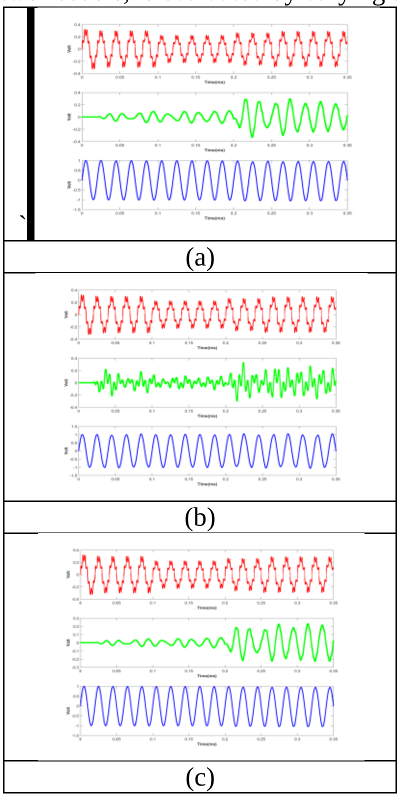
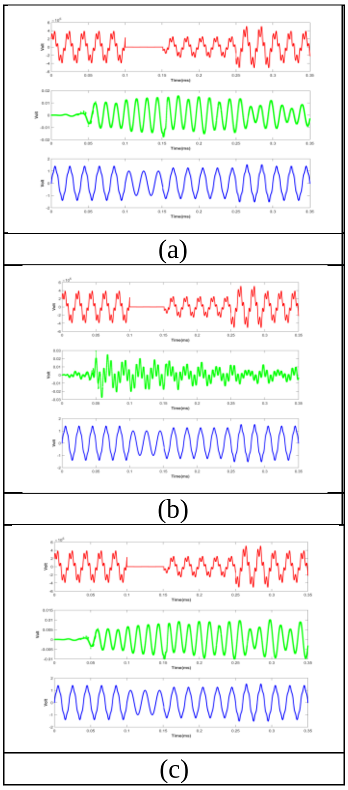


Figure 13. Performance of proposed MC-UPQC in terms of (a) BOA-FLC-MC-UPQC, (b) BS-BSO-FLC-MC-UPQC, and (c) BS-BOA-FLC-MC-UPQC using feeder 1.

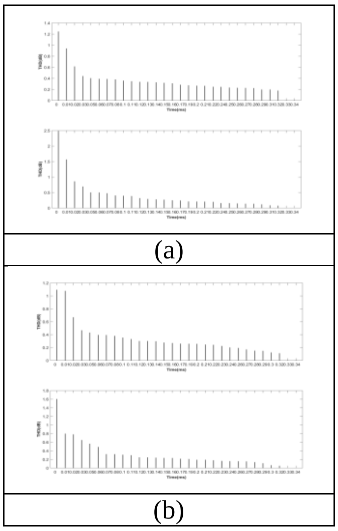


(a) (b) (c)

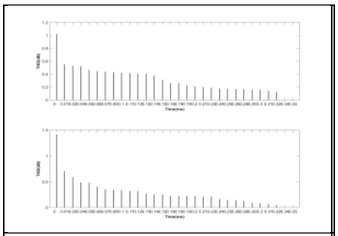
Figure 14. Performance of proposed MC-UPQC in terms of (a) BOA-FLC-MC-UPQC, (b) BS-BSO-FLC-MC-UPQC, and (c) BS-BOA-FLC-MC-UPQC with the help of feeder 2

5.5 Harmonic Analysis

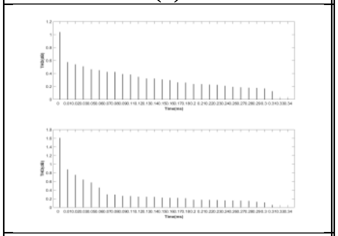
The harmonic analysis on BS-BOA-FLC-MC-UPQC over the conventional models and the traditional heuristic-based FLC-MC-UPQC connected with feeders 1 and 2 is displayed in Fig. 15 and Fig. 16, respectively. Fig. 15 displays the THD of the general NN-MC-UPQC, FLC-MC-UPQC, MC-UPQC, and BS-BOA-FLC-MC-UPQC at various seconds. The proposed BS-BOA-FLC-MC-UPQC is decreased over the sequence of time than all the traditional models. At 0.34sec, for feeder 1, the THD of the developed BS-BOA-FLC-MC-UPQC is 99.99% better than general MC-UPQC, FLC-MC-UPQC, and NN-MC-UPQC respectively. Similarly, for feeder 2, at 0.33sec, the THD of the developed BS-BOA-FLC-MC-UPQC is 99.98% improved than general MC-UPQC, FLC-MC-UPQC, and NN-MC-UPQC. While considering Fig. 16, the THD of the suggested BS-BOA-FLC-MC-UPQC for feeder 1 at 0.34sec is 99.99% more progressed than BOA-FLC-MC-UPQC, and 75% progressed than BS-FLC-MC-UPQC. Moreover, in the case of feeder 2, for 0.34sec, the THD of the proposed BS-BOA-FLC-MC-UPQC is 99.99% surpassed than BOA-FLC-MC-UPQC and 80% higher than BS-FLC-MC-UPQC. Hence, it is clearly understood that the THD is minimized in the proposed BS-BOA-FLC-MC-UPQC than the conventional models and the existing heuristic-oriented FLC-MC-UPQC when it is connected with feeder 1 and feeder 2.



(a) (b)

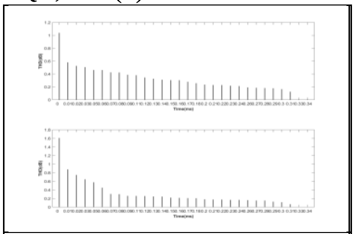


(c)

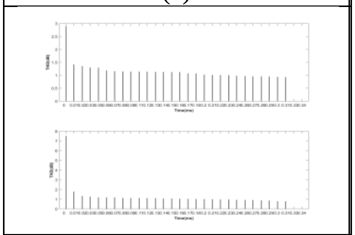


(d)

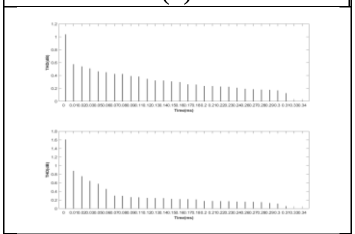
Figure 15. The harmonic analysis of designed MC-UPQC in terms of (a) General MC-UPQC system, (b) FLC-MC-UPQC, (c) NN-MC-UPQC, and (d) BS-BOA-FLC-MC-UPQC, for feeder 1 and 2



(a)



(b)



(c)

Figure 16. The harmonic analysis of recommended MC-UPQC in terms of a) BOA-FLC-MC-UPQC, (b) BS-BSO-FLC-MC-UPQC, and (c) BS-BOA-FLC-MC-UPQC for feeder 1 and 2

5.6 Convergence analysis

The convergence analysis of the recommended MC-UPQC method is shown in Figure 17. The proposed BS-BOA-FLC-MC-UPQC offers better results based on the least cost. Here, the cost function using the proposed BS-BOA-FLC-MC-UPQC is minimized while increasing the number of iterations. The cost function of the concerning UPQC is decreased at the final iteration. At the 20th iteration, the BS-BOA-FLC-MC-UPQC obtains a better rate of convergence, 0.09% better than BOA and 5.8% better than the BSO algorithm. Therefore, the proposed BS-BOA-FLC-MC-UPQC performs better for all the iterations when compared with other heuristic algorithms.

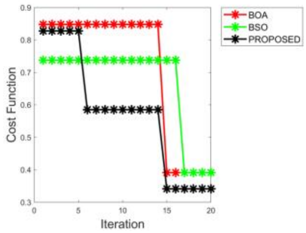


Figure 17. Convergence analysis of suggested MC-UPQC to enhance the power quality

5.7 Analysis of Computational time

The time analysis of the proposed and conventional MC-UPQC is shown in Table 4. The proposed BS-BOA takes 4.34% and 8.96% minimum time than the BOA and BSO, respectively. Hence, the proposed BS-BOA takes lesser time to completion of the designed model than all the existing methods.

Table 4. Time analysis of the designed MC-UPQC

Methods	BOA	BSO	Proposed BS-BOA
Time(sec)	138	145	132

5.8 Comparison of the proposed and conventional MC-UPQC with the existing methods

The comparison of the suggested and conventional MC-UPQC with the existing algorithms is shown in Table 5. For feeder 1, the proposed BS-BOA performs 26.36%, 19.18%, and 17.18% better than Fuzzy, BOA-fuzzy, and BSO-fuzzy. Therefore, the proposed BS-BOA performs better than all the traditional methods.

Table 5. Comparison of the proposed and conventional MC-UPQC to improve power quality

	Feeder 1	Feeder 2
Before Compensation	-23.687	-9.0726
Fuzzy (Rajani and Raju 2013)	-20	-11.025
BOA-fuzzy (Arora and Singh 2018)	-21.952	-20.628
BSO-fuzzy (Chen et al. 2018)	-25.749	-26.535
Proposed BS-BOA	-27.161	-26.105

5.9 Harmonic analysis based on the THD level

The harmonic analysis of the proposed and conventional MC-UPQC is shown in Table 6 and Table 7. From Table 7, the proposed BS-BOA-FLC-MC-UPQC model secured 1.5001, 0.88083, and 0.82883 lower than General MC-UPQC, FLC-MC-UPQC, and NN-MC-UPQC, respectively. Table 6 shows the THD level of the general MC-UPQC, FLC-MC-UPQC, NN-MC-UPQC, and BS-BOA-FLC-MC-UPQC at various seconds. Accordingly, Table 7 shows the THD level of the general BOA-FLC-MC-UPQC, BS-BSO-FLC-MC-UPQC, and BS-BOA-FLC-MC-UPQC at various seconds. Hence, it is proved that the suggested BS-BOA-FLC-MC-UPQC is better than the other conventional algorithms.

Table 6. THD values of the total harmonic distortion 1 of the proposed MC-UPQC

	General MC-UPQC	FLC-MC-UPQC	NN-MC-UPQC	BS-BOA-FLC-MC-UPQC
Mean	15.001	8.8083	9.1883	8.803

Table 7. THD values of the total harmonic distortion 2 of the proposed MC-UPQC

	BOA-FLC-MC-UPQC	BS-BSO-FLC-MC-UPQC	BS-BOA-FLC-MC-UPQC
Mean	11.347	34.333	8.803

6. Conclusion

This paper has designed an optimally controlled MC-UPQC that handled the issues in the power quality in the distribution system. This problem has been solved based on SRF theory. In general, the MC-UPQC involved two series VSC, where the power was transferred from one feeder to another that eliminated the "voltage sag, swell, interruption and transient response of the system." The proposed model has adopted the control schemes of MC-UPQC based on optimized FLC in SRF. The optimized FLC was utilized in the designed method of BS-BOA. The membership limit was optimized by the designed BS-BOA, from which the control rules were generated for inputs. The major benefit of the optimized FLC-based MC-UPQC was its quick behavior in minimizing the THD on the source and load side voltages considered based on both feeders. The comparative analysis was done over the traditional controllers to validate their effectiveness. From the analysis, the THD of the proposed BS-BOA-FLC-MC-UPQC is 99.99% better than BOA-FLC-MC-UPQC and 80% better than BS-FLC-MC-UPQC. Hence, the proposed controller overcomes the existing model in enhancing the power quality in MC-UPQC under the distribution system. A few limitations of the designed method to improve the power quality are shown here. In MC-UPQC, the output of the voltage level is low. The reconfiguration for optimal sizing of distributed generators is a complex task. The power grids are quite challenging due to the unbalanced power flow. In a larger network, the MC-UPQC is connected to the main grid is a complex task. In the future, multiphase balancing power flow will be utilized in the distributed system. The renewable energy sources and the passive filters will be adapted to control the power in the MC-UPQC model. Consequently, we will try to enhance the flexibility and capacity of the MC-UPQC model in further development.

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Reviewed Manuscript Title:

Optimal Operation of Multi-Converter-UPQC for Power Quality Improvement in Distribution System using Optimized Fuzzy Logic Controller

1. Figure 1, Figure 2, Figure 3, Figure 4, Figure 5 and all the fonts are too small.
2. Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, and all the fonts are too small.
3. Figure 11, Figure 12, Figure 13, Figure 14, Figure 15, Figure 16, and all fonts are too small.
4. In Figure 11, Figure 12, Figure 13, and Figure 14, the authors cannot explain the types of system disturbances based on the performance of the method and proposed MC-UPQC as previously explained in the abstract section? Does it include sag, swell, or interruption?
5. Reviewer has difficulty seeing the wave type display i.e. Source Voltage Waves, Injection/Series Voltage Waves, and Load Voltage Waves in Figure 11, Figure 12, Figure 13, and Figure 14 because all display Figures and fonts are too small to be seen by normal eyes.
6. The reviewer has difficulty seeing the appearance of the THD spectra curve i.e. Source Voltage THD, Injection/Series Voltage THD, and Load Voltage THD in Figure 15 and Figure 16 because all the display pictures and fonts are too small to be seen by normal eyes.
7. In Table 6 and Table 7, all the THD values of the new configurations and methods proposed by the authors (proposed MC-UPQC and BS-BOA-FLC-MC-UPQC) are 8.803%, which means they are still above the IEEE 519 standard of 5%.
8. In the conclusion section, the performance of UPQC whatever of the proposed combinations and methods in general i.e. (a) reducing the THD of the load voltage and improving (stabilizing) the magnitude of the load voltage due to voltage sags, swells, and interruptions at the source bus and (b) reducing the THD of the source current due to existence of non-linear load on the load side. The author failed to show the reader about improving all of these parameter values, so the main goal of UPQC implementation in a system finally is not to be achieved.

Reviewer Recommendation and Comments for Manuscript Number UCBS-2022-0758

Optimal Operation of Multi-Converter-UPQC for Power Quality Improvement in Distribution System using Optimized Fuzzy Logic Controller

Original Submission
Amirullah Amirullah, Doctoral Degree Reviewer 3

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Reviewer Comments to Author

1. Figure 1, Figure 2, Figure 3, Figure 4, Figure 5 and all the fonts are too small.
2. Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, and all the fonts are too small.
3. Figure 11, Figure 12, Figure 13, Figure 14, Figure 15, Figure 16, and all fonts are too small.
4. In Figure 11, Figure 12, Figure 13, and Figure 14, the authors cannot explain the types of system disturbances based on the performance of the method and proposed MC-UPQC as previously explained in the abstract section? Does it include sag, swell, or interruption?
5. Reviewer has difficulty seeing the wave type display i.e. Source Voltage Waves, Injection/Series Voltage Waves, and Load Voltage Waves in Figure 11, Figure 12, Figure 13, and Figure 14 because all display Figures and fonts are too small to be seen by normal eyes.
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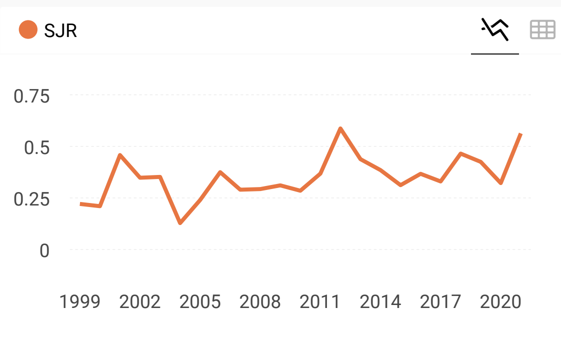

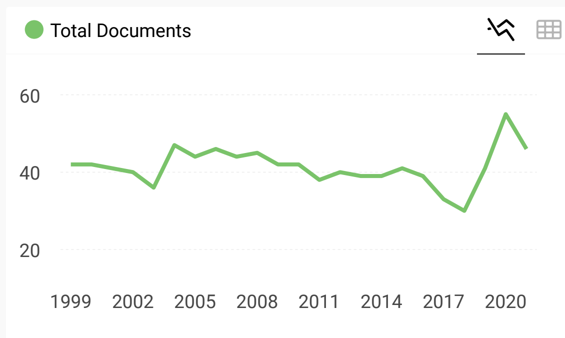

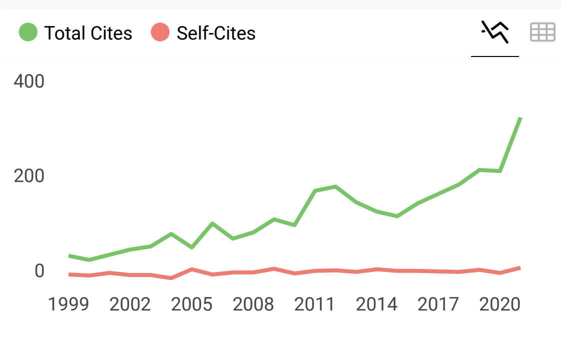

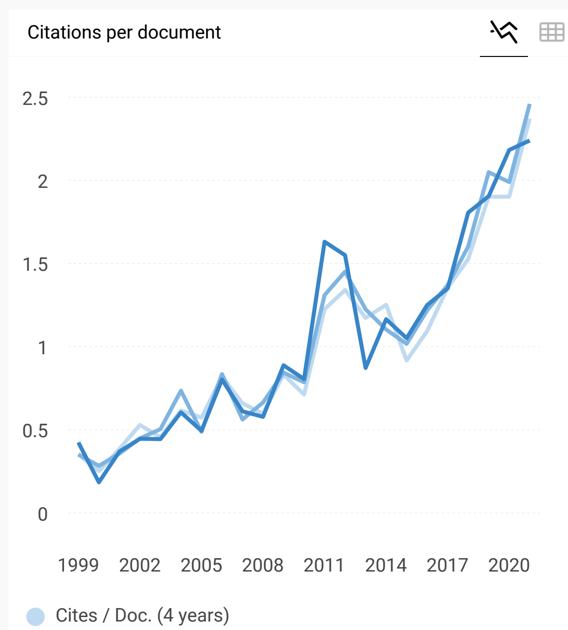

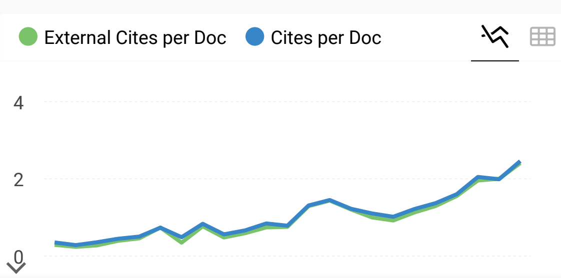

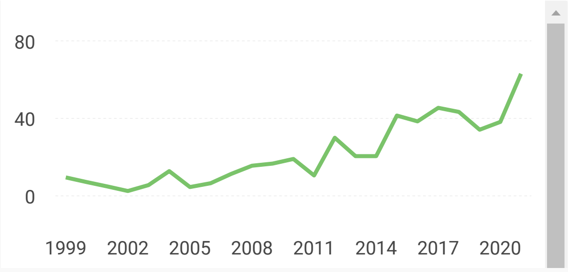

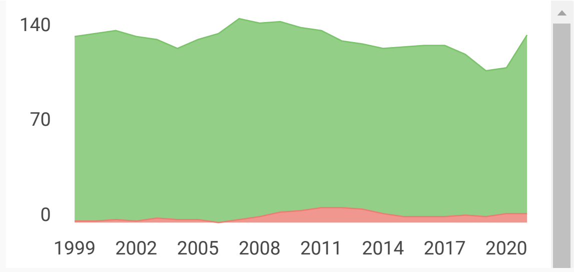

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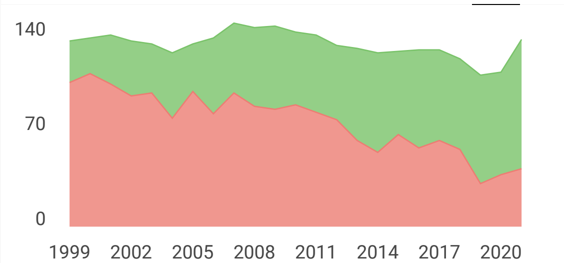

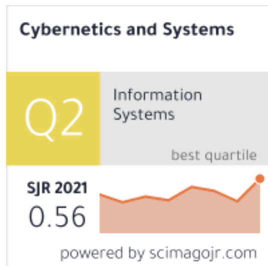

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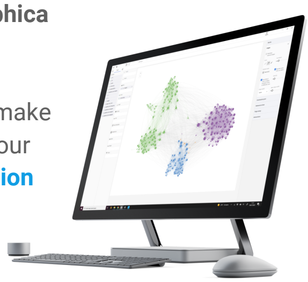

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