



Improvement of power quality in power system using hybrid automata supervisory controller

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Received 30 January 2023; Received in revised form 1 September 2023; Accepted 21 November 2024

Keywords

Discrete Event System (DES);
Hybrid Automata in Power Quality (HAPQ);
Total Harmonic Distortion of Voltage (THD_v);
Hybrid Automata (HA) modeling;
Supervisory controller.

Abstract

This paper proposes a systematic approach to the design of a supervisory control scheme using a new method of Hybrid Automata in Power Quality (HAPQ) improvement. In order to achieve better power quality, a model is introduced for optimal controller use, and the general behavior of the power system is presented with Hybrid Automata (HA). The formalism of a hybrid system contains continuous dynamics and discrete switching behavior in a control and modeling framework. Hence, it can facilitate achieving a detailed description of the system while highlighting safety issues in the criteria of system design. This study uses a power system HA model as a Discrete Event System (DES) plant and controller. DESs are utilized to examine HA models along with the presence and absence of disturbances and control features such as non-linear load, Static Compensator (STATCOM), and filter. In order to examine the power quality and voltage stability, power quality indicators such as Total Harmonic Distortion of Voltage (THD_v), eigenvalues, bus voltage, and stability theory of switched systems are evaluated. The simulation results reveal the effective performance of the proposed supervisory controller HAPQ model to enhance power quality and stability in power systems.

1. Introduction

In distribution networks, unbalanced Distributed Generation (DG), increasing non-linear loads, and single-phase/unbalanced loads lead to power quality challenges [1]. The extensive use of power electronics-based equipment and non-linear loads at the Point of Common Coupling (PCC) generates harmonic currents that deteriorate the quality of the electric power. Moreover, from the system operator's viewpoint, excessive higher harmonic levels are undesired and permissible limits for each harmonic and Total Harmonic Distortion (THD) (both in voltage and current) are given by the international standards [1,2]. For example, more efficient loads such as Light-Emitting Diodes (LED), Adjustable Speed Drives (ASD), fridges, etc., produce high current harmonics in the residential distribution system, and it is expected that the residential system, Total Harmonic Distortion of Voltage (THD_v) will reach 5% soon in North America [3]. Therefore, with the increase in the number of distorted loads, the power quality decreases, and the most

common power quality issues today are harmonic distortion, voltage reduction, and low power factor [4]. Therefore, reactive power, harmonic pollution, voltage flicker and also three-phase imbalance in the power grid face serious challenges [5,6]. Harmonic currents in the distribution system can cause harmonic distortion, low power factor, additional network losses, heating in electrical equipment, as well as vibration and noise in machines and equipment sensitive to faults [7]. In recent years, many devices have been used to improve power quality. The Static Compensators (STATCOMs), whose structures are similar to active power filters, can be used to compensate harmonics. Also, STATCOMs can supply reactive power and can be used to compensate harmonics, but the effect of STATCOM presence on reducing harmonics should be investigated.

In recent years, much research has addressed the issue of improving power quality. Custom power devices are suggested as one of the best solutions to improve the power

To cite this article:

F. Forouzesh, M. Eslami, M. Jafari Shahbazzadeh, A. Abdollahi "Improvement of power quality in power system using hybrid automata supervisory controller", *Scientia Iranica* (2025) 32(19) 7526. <https://doi.org/10.24200/sci.2023.61859.7526>

quality in the electrical system [8]. Hence, STATCOM is proposed in recent years, which is connected in shunt with the load. STATCOM can supply reactive power such that source currents will be balanced with sinusoidal and near-unity power factors [8]. Cost-effective elucidation for the reactive power compensation and load unbalance in the transmission system can be effectively achieved using STATCOM and other Flexible AC Transmission System (FACTS) devices [8]. STATCOM is a significant device with a wide range of problem-solving capabilities among all FACTS in both transmission and distribution levels. Some power quality aspects, such as reactive power compensation of linear loads, better THD performance, and power factor improvement, are achieved as a consequence of using STATCOM [9]. STATCOM with a control strategy can lead to maintaining power quality with high standards, minimizing THD, and improving power factors [8]. Also, the Distribution Static Compensator (D-STATCOM) is a shunt compensator in distribution systems, and one of the most important tasks is to improve the imbalance and reduce and eliminate the harmonics of nonlinear loads [10-12]. The fuzzy logic controller was used in the control system of D-STATCOM [10]. This equipment is necessary for eliminating the harmonics in the distribution systems [10]. The main drawback of using a metaheuristic algorithm to tune the gains of conventional controllers is that it requires basic data and complex calculations. The compensator implemented in [11] is suitable for three-phase three-wire systems and harmonic compensation and is not able to compensate for neutral current [11]. The main idea in [13] is performance improvement of a system-level harmonic using a harmonic power flow controller [13].

Such behavior is characterized by interactions between continuous dynamics and discrete events. Some components drive the continuous dynamics, while others, such as protection devices, manifest event-driven discrete dynamics. It should be mentioned that the power system operation is categorized into different states, namely normal, alert, emergency, and restorative states. Therefore, power systems can be introduced as an appropriate example of a hybrid system [14]. Therefore, hybrid system reachability for power systems' stability and power quality analysis is proposed in [15].

Hybrid systems are dynamic systems interacting with continuous and discrete-valued states [16]. Hybrid system reachability is widely deployed for verification of system safety properties whose behaviors are represented by a hybrid system mathematical model [16-18]. Power system dynamics and control is contained hybrid nature [19]. Reference [19] implies that they are regarded as a dynamic interaction between continuous behaviors of frequency or voltage and discrete controls such as protective relays and switching equipment. Therefore, power system control can be considered a typical application of safety verification for hybrid systems [20].

In [21], a systematic approach for designing and analyzing a supervisory control scheme in power systems using the Hybrid Automata (HA) model is introduced. The proposed approach is derived for optimal controller application, and the power system's overall behavior is modeled using HA to enhance its stability. In [21], a power system HA model is employed as a Discrete Event Systems (DESs) plant and controller. Also, the discrete events used in

[22], in addition to [21], include generator outages and control equipment like the capacitor bank and Under-Load Tap Changer Transformers (ULTC) which use hybrid modeling to improve network stability. The HA supervisory controller design approach has been effective in the presence of DG [22].

Harmonic analysis has not been done to this extent and accuracy in previous papers and studies. In this paper, a new framework is presented to model power systems using Hybrid Automata in Power Quality (HAPQ) improvement. The advantage of the proposed methodology is regarded to easier and more accurate handling of power quality analysis. The proposed HAPQ technique is capable of straightforward power quality and stability analysis, THD_v investigation for all possible discrete states and designing an HA control graph for the system, while a supervisory controller is implemented.

The supervisory control of DES can be designed to be hierarchically structured. Implementation of the abovementioned approach in such a control problem is also discussed in this paper.

In the proposed method, discrete events including the presence and absence of disturbances and power quality control elements, nonlinear load, STATCOM, and filter are utilized to present the hybrid model. Power quality indicators are also examined for eight System modes (Sm). In this paper, first, a scenario of Sm (Nonlinear Load (NL Load), stat, filter) is defined for various Sm. The controller is designed by HA modelling under a disturbance resulting from a NL Load. The supervisory controller is intended to use STATCOM (stat) and a filter. The DES is presented and the overall HA modelling for each system consisting of eight modes is performed. In order to confirm the effectiveness of the proposed method, the simulation results are compared with well-established algorithms [23-37].

The simulation results demonstrate that the control process of HAPQ is implemented and examined in the IEEE 33-bus system and test system, as well as the South of Kerman Electrical Distribution (SKED1) test system with actual data [38]. In brief, the main contributions of this paper can be summarized as:

- This paper attempted to model a power system based on HA. Here, a controller is designed to supervise the HAPQ and stability in power systems;
- DESs, including the presence and absence of disturbances and control features, nonlinear load, STATCOM, and filter, are utilized;
- Power quality indicators such as THD_v, bus voltage, eigenvalues, and switched systems' stability theory are employed in order to evaluate power quality as well as voltage stability.

The rest of this paper is organized as follows: Section 2 describes the hybrid system and HA. Sections 3 and 4 examine indicators such as THD_v and voltage stability for Sm and present the proposed HAPQ model for the Sm scenario. Here, a supervisory controller for the aforementioned scenario is also designed. In Sections 5 and 6, simulation results are discussed. Finally, concluding remarks are drawn in Section 7.

2. Hybrid systems

A hybrid dynamic system behavior is influenced by continuous

and discrete dynamics. As an important feature of these systems, some dynamics are time-driven while the other ones are event-driven. In time-driven systems, the mechanism of the Sm change is based on differential equations where the modes vary over time. In event-driven and DES systems, the changes in the Sm depend on the events that occur [39, 40].

The communication between two continuous and DES systems is facilitated by an interface and communication signals. Some types of hybrid dynamic systems include the HA machine, timed Petri nets and switched systems [40].

2.1. Hybrid Automata (HA)

In this paper, the HA method is utilized to model the system. The main purpose of mathematical modeling of a physical process is to make the problem understandable for designing the controller. HA can be expressed as shown in Eq. (1) [40]:

$$H = (Q, \nu, f, \text{Init}, \text{Inv}, \theta, G, R), s, \quad (1)$$

- Q is a limited set of system discrete modes;
 $Q = \{q_1, \dots, q_k\}$, $q \in Q$;
- ν refers to a limited set of continuous states of the system, and x is introduced as the continuous state space;
- $\dot{x} = f(q, x)$ presents the continuous dynamics, and f denotes the functions related to the system continuous dynamics $(q, x) \in Q \times \nu$;
- $\text{Init} \subseteq Q \times R^n$ is a set of the system's initial modes and conditions;
- $\text{Inv}: Q \rightarrow 2^{R^n}$ is the description of the location's characteristics. It is a prerequisite for staying in or passing through the continuous modes of the system. There is a continuous dynamic for each location as long as the prerequisite related to the location is mandatory;
- $\theta \subset Q \times Q$ is the interface of the system's transitions graphically depicted as arcs between discrete modes;
- $G: \theta \rightarrow 2^{R^n}$ is the system guard prerequisite, which is applied to the arcs of HA model. It constrains the continuous dynamics' function;
- $R: \varepsilon \rightarrow 2^{R^n} \times 2^{R^n}$ resets the map to its initial mode. This mapping can be utilized to find the continuous state location in the subset of the continuous state space that is not used in the power system [40].

3. Power quality evaluation without a controller

In order to evaluate the power quality, it is crucial to peruse the system behavior when subjected to a non-linear load disturbance. In this section, the power quality is examined for different Sm as follows:

- (1) Normal conditions;
- (2) In the presence of non-linear loads;
- (3) In the presence and absence of non-linear load and STATCOM;
- (4) In the presence and absence of non-linear load and filter;
- (5) In the presence and absence of STATCOM and filter.

The methods which are employed to monitor the system power quality and voltage stability include:

- THD_v and harmonic distortion of the buses [41];
- The voltage of the buses [42], [43] and [44];
- The eigenvalues of a system [42], [43] and [45];
- The stability theory of the switched systems [46,47]. d can be examined for power quality assessment when the controller is considered.

4. HAPQ controller design and modeling

The purpose of designing a HAPQ controller is to improve the power quality and stability. The controller inputs can be mentioned as:

- (I) The voltage of sensitive buses: The STATCOM control is adjusted to the voltage of the most sensitive buses. The standard bus voltage deviation is $\pm 5\%$. It means that a voltage $1.05 < V_{bus} < 0.95$ is standard and permitted [2,42,48];
- (II) The current of the sensitive load with STATCOM and filter: The control of THD_v is adjusted to the THD_v of the bus, while the standard THD_v deviation in each bus is less than 5% [23]. If the power system is subjected to a non-linear load and the THD_v exceeds the allowable limit, the STATCOM is applied. According to the flowchart of the proposed HAPQ controller in Figure 1(b), THD_v with the presence of a STATCOM should be checked. According to the type of non-linear load and power systems with special conditions, the effect of STATCOM presence in reducing THD_v should be investigated.

If the THD_v is not yet within the allowable range, a filter will be called. Figure 1 depicts the hierarchy of the proposed controller operation.

4.1. HA modeling and performance of HAPQ supervisory controller under non-linear load

The discrete states of the system are introduced for HA modeling. These are a combination of discrete events, including disturbances of non-linear load and power quality control elements such as STATCOM and filter, as shown in Table 1.

According to the events in Table 1, the number of system states can be achieved equal to $2^3=8$. Here, the power system is represented by "S" and "m" expresses the mode number. Table 2 presents the above-mentioned eight modes occurring for the system. Each mode has a specific continuous dynamic. For example, mode "S3" represents the continuous dynamics of the system with the presence of a non-linear load and STATCOM, while the filter is not considered.

The operation of the monitoring controller can be explained as follows. First, the power system is considered in the normal mode, i.e., S1. When a non-linear load is

Table 1. DESs with the scenario of Sm (NLLoad, stat, filter).

Event name	Value	Event explanation
NL Load	1	Presence of non-linear load
	0	Lack of non-linear load
Stat	1	Lack of non-linear load
	0	Presence of STATCOM
Filter	1	Presence of filter
	0	Lack of filter

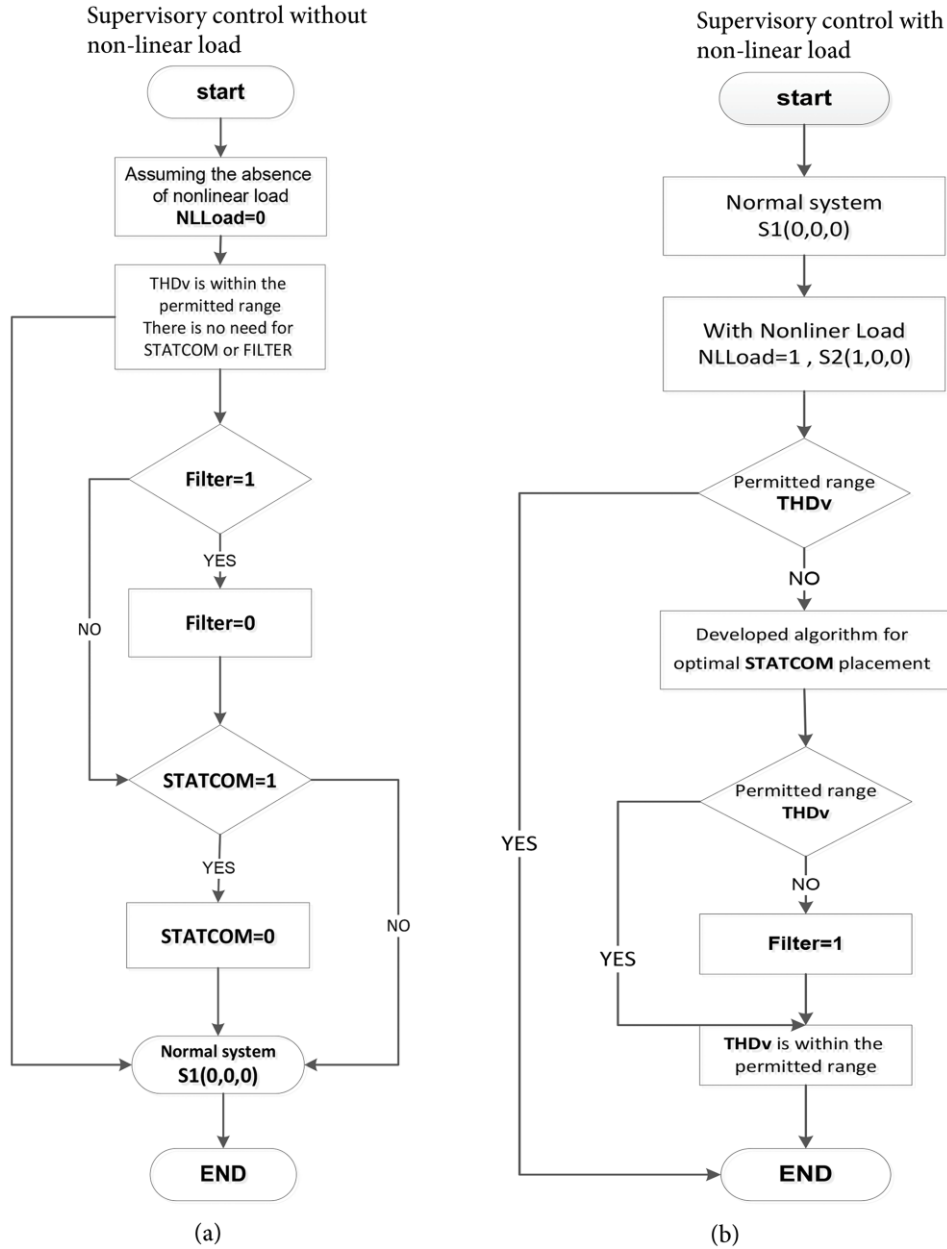


Figure 1. Flowchart of the proposed HAPQ controller: (a) without non-linear load; and (b) with non-linear load.

connected to the system, the S_m changes from S_1 to S_2 and THD_v index rises above the allowable range of 5%. In order to handle the harmonic issue, the STATCOM first enters and the system status changes to S_3 . If THD_v index is still not within the allowable range, a filter is called and the system is included in S_4 . The transitions between 8 states are comprehensively shown in Figure 2.

The HA model of the system is formulated as shown in Eq. (1) [40]. Q is a set of discrete states as shown in Eq. (2):

$$Q \in \{S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8\}, \quad (2)$$

where v is the set of the system's continuous variables and defined in Digsilent Power Factory (DPF) software as shown in Eq. (3) [49]:

$$v \in \{\phi, speed, psie, psiD, psiX, psiQ\}. \quad (3)$$

The description of continuous variables is provided in Table 3. In steady-state systems, the eigenvalues are obtained with modal analysis in DPF software and after that, the transfer function can be obtained.

The continuous dynamics of the system are represented as $\dot{x} = A_i(x)$. In order to obtain A_i in Eq. (4), given the eigenvalues corresponding to each state, the transfer function's denominator for the system is obtained by Eq. (5). Then, A for each system state can be achieved by the canonical realization of its controller. More detailed explanations are provided in Appendix A. n is considered as the number of eigenvalues.

$$A_i \in \{A_1, A_2, A_3, \dots, A_8\}, i=1,2,\dots,8, \quad (4)$$

$$A_i = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \dots & 1 \\ -a_0 & -a_1 & -a_2 & \dots & -a_{n-1} \end{bmatrix}$$

$$P_i(S) = S^n + a_{n-1}S^{n-1} + \dots + a_1S + a_0. \quad (5)$$

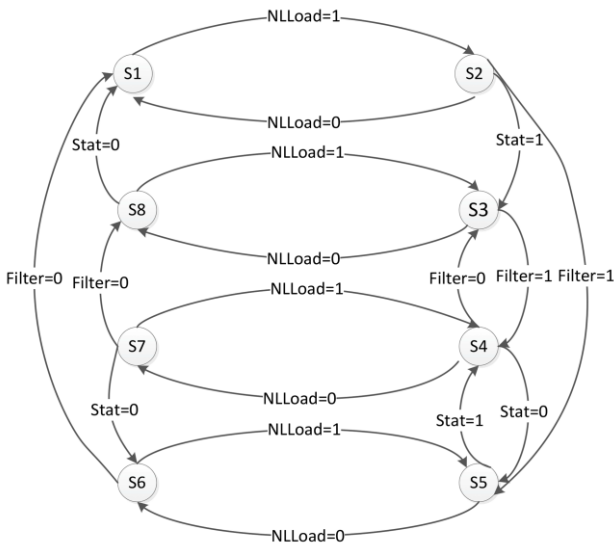
Inv is expressed as shown in Eq. (6):

Table 2. System modes with scenario Sm (NLLoad, stat, filter).

Sm	NLLoad	Stat	Filter
S1	0	0	0
S2	1	0	0
S3	1	1	0
S4	1	1	1
S5	1	0	1
S6	0	0	1
S7	0	1	1
S8	0	1	0

Table 3. Continuous variables [49].

Name of variables	Unit	Explanation
Speed	p.u	Speed
Phi	Rad	Rotor angle
Psie	p.u	Excitation Flux
PsiD	p.u	Flux in D - Winding
Psix	p.u	Flux in X - Winding
psiQ	p.u	Flux in Q - Winding
Speed	p.u	Speed

**Figure 2.** HAPQ graph model for the Sm scenario.

$$Inv \in \{ NLLoad = 0, NLLoad = 1 \}. \quad (6)$$

At the first time, the system operates in S1 and remains in this mode until a non-linear load is added to the system. The initial state of the system is expressed as Init=S1. Under the same prerequisite intended for the HA arcs, system guards are expressed as Eq. (7):

$$G \in \{ NLLoad = 0, NLLoad = 1, Stat = 0, Stat = 1, Filter = 0, Filter = 1 \}. \quad (7)$$

The summary of the implementation of the methodology is shown in Figure 3.

5. Simulation results for the first case study

The proposed structure is applied to the IEEE 33-bus distribution system, as shown in Figure 4 [50]. The parameters of this standard 12.66 kV power distribution system with 33-buses and a feeder with four lateral branches are described in [51].

5.1. Evaluating steady-state power quality for discrete states without a controller

5.1.1. Studying the power quality with a non-linear load in the network without the controller

The total peak load of the IEEE 33-bus test system is 3715 KW. In this section, all calculations are performed by DPF software, and programming is executed using DigSilent Programming Language (DPL) code and content.

In S2, a non-linear load is incorporated into the test system. Filters and STATCOMs are not considered, and the harmonic issues of voltage, current, and voltage profiles are checked.

The type, location, and percentage of non-linear loads are presented in Table 4. In this case study, the harmonic spectrum is illustrated for three different types of non-linear loads, such as fluorescent, PC workstation, and ASD, as shown in Table 5. The non-linear loads are located in buses (14, 22, 24, and 30). According to the IEEE 519 standard, THD_v should be less than 5%, and each harmonic should be limited to 3%. As a consequence of implementing the harmonic load flow, the Harmonic Distribution voltage (HD_v) of 17, 19, and 23 orders at Bus 14 is increased by more than 3%, which indicates a harmonic problem in the system. The highest voltage harmonic is the 23-order harmonic. The other buses of the IEEE 33-bus system are within the permitted harmonic range, as shown in Figure 5(a). THD_v of buses 10 to 13 is above 5%, as shown in Figure 5(b). There is a voltage drop problem on the buses. The system eigenvalues are obtained to analyze the system's stability in the presence of non-linear loads. The system eigenvalues are acquired after performing the system Modal calculations, as given in Table 6. Therefore, the system has a harmonic problem in the presence of a non-linear load, and several buses suffer from voltage drops, but the system remains stable.

5.1.2. Evaluating the power quality with a non-linear load and STATCOM in the network without the controller

This section examines S3 as another discrete state of the system. Indeed, a non-linear load is connected to the system, and only STATCOM is considered in the network. The Imperialistic Competition Algorithm (ICA) is employed for STATCOM and filter allocation to maintain voltage stability and reduce losses and THD_v due to its high speed and accuracy.

STATCOM allocation is a mixed-integer non-linear optimization problem. The objective function is based on minimizing the system's active power losses and THD_v [52]. The first term of the Objective Function (F_1) is related to the reduction of power losses, defined as Eq. (8). The second term of the Objective Function (F_2) is related to the reduction of THD_v, defined as Eq. (8). The maximum allowed value of the F_2 range is 5%. The third term of the Objective Function (F_3) is the permissible value of the voltage range between at least 0.95 and 1.05, as shown in Eq. (8):

$$F_1 = \text{Min} \sum_{i=0}^n (I_i) \cdot r_i,$$

$$F_2 = \text{Min THD}_v = \frac{\sqrt{\sum_{n=2}^N V_n^2}}{V_1} \times 100\%,$$

$$F_3 = \text{Min SUM}(\text{abs}(V_n - V_i)) \text{ for } i=2,3,\dots,N_B, \quad (8)$$

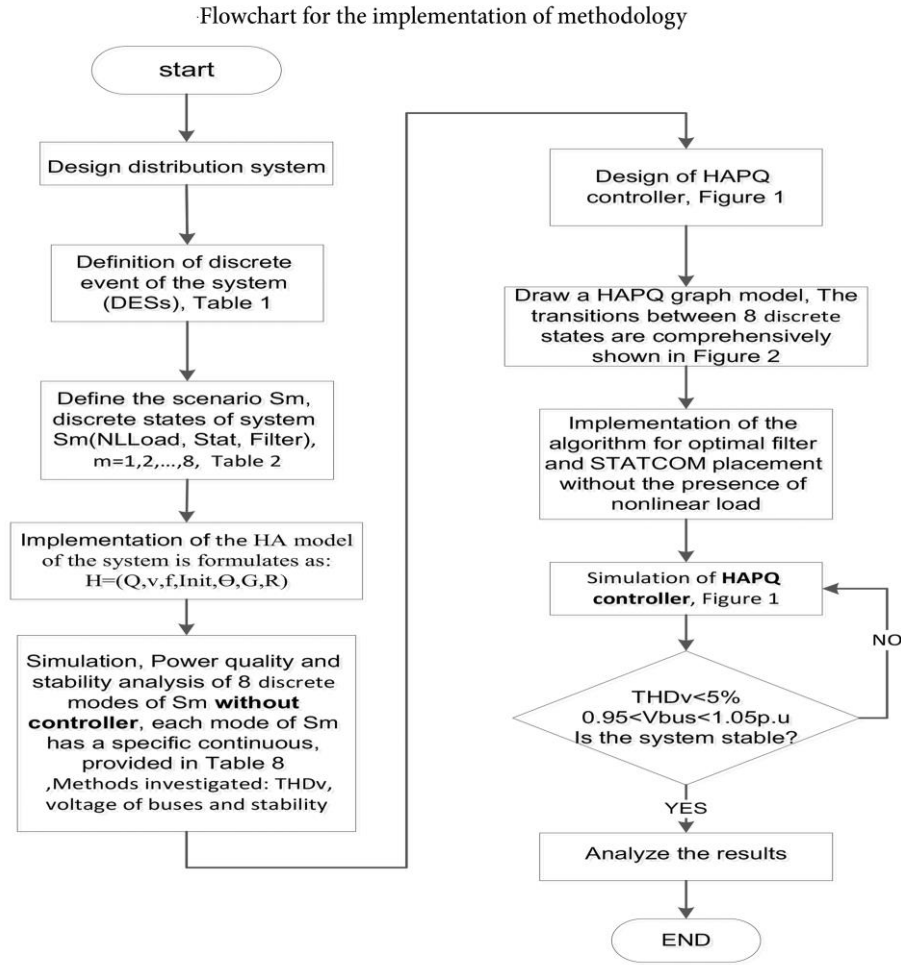


Figure 3. Flowchart for the implementation of the methodology.

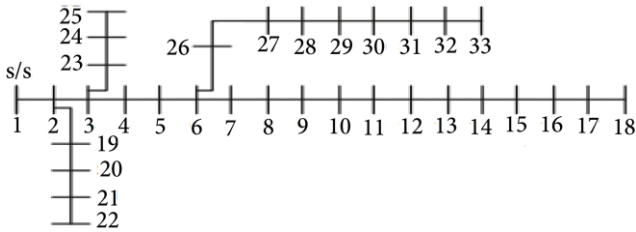


Figure 4. Standard IEEE 33-bus [50].

Table 4. Non-linear loads [23].

Bus No.	Non-linear load type	Percentage (%)
14,22,24	Fluorescent	43
	PC Workstation	29
	Adjustable Speed Drive (ASD)	29
30	ASD	65

where V_n is the nominal voltage. I_i and r_i are the current and resistance of line i .

In order to satisfy the system demand, the following equations are considered [52]:

$$P_{sys} + P_{Stat} = P_d + P_{loss}, \quad (9)$$

$$Q_{sys} + Q_{Stat} = Q_d + Q_{loss}, \quad (10)$$

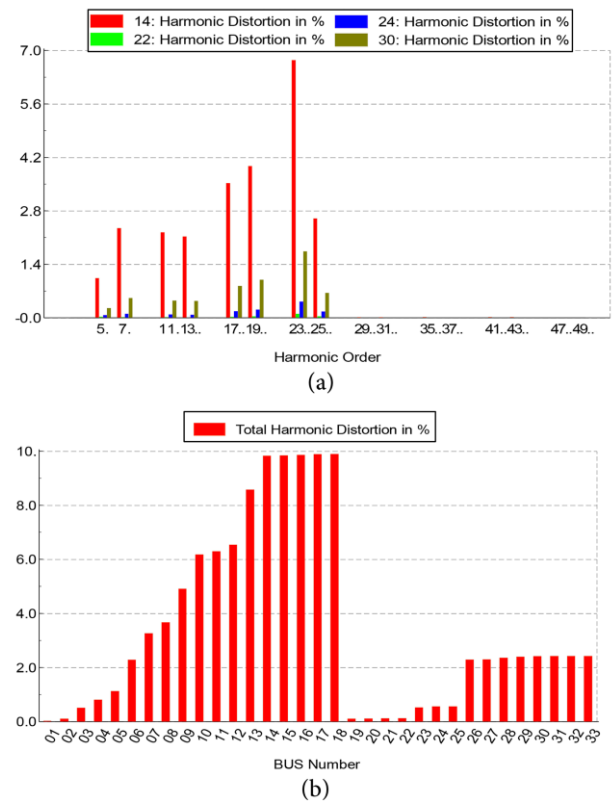


Figure 5. (a) HDv of 5 to 25 at Buses 14, 22, 24, 30 and (b) THDv of buses with non-linear load.

Table 5. Harmonic spectrums of the non-linear loads.

Harmonic order	PC Workstation [24] Mag.(%)	ASD phase (deg.)	Fluorescent [24] Mag. (%) - (33-bus)	Mag. (%) - SKED [24]	Phase (deg.)	Mag. (%)	Phase (deg.)
1	100	0	100	100	0	100	-2
5	3.9	-150	5	82.8	-135	3.9	-150
7	1.4	-28	8	77.5	69	2.9	-73
11	0.9	-176	5	46.3	-62	1.4	6
13	0.5	-60	4	41.2	139	0.8	29
17	0.5	139	5	14.2	9	0.2	-17
19	0.3	-126	5	9.7	-155	0.5	-56
23	0.3	112	7	1.5	-158	0.2	-65
25	0.3	-155	2.5	2.5	98	0	0
29	0.4	38	0	0	0	0	0
31	0.4	134	0	0	0	0	0

Table 6. The eigenvalues of the system with nonlinear loads.

Row	Eigenvalue
1	-1+j0
2	-10+j0
3	-1+j0
4	-10+j0
5	0+j0
6	-0.00012+j0
7	0+j0

where P_{sys} and Q_{sys} represent the active and reactive power of the main system, respectively. P_{Stat} and Q_{Stat} signify the active and reactive power of the STATCOM, respectively. P_d and Q_d indicate the total active and reactive power demand, respectively. P_{loss} and Q_{loss} demonstrate the total system's active and reactive power losses, respectively.

In this optimization problem, the system voltage constraint is also considered as shown in Eq. (11) [52]:

$$V_{min} \leq V_{sys}^i \leq V_{max}, \quad (11)$$

where V_{sys}^i is the voltage of i th bus. In Eq. (11), V_{min} and V_{max} represents the lower and upper bounds of the voltage, which is considered $1 \pm 5\%$ of the nominal voltage value.

The thermal capacity limits of the network's lines are considered as shown in Eq. (12) [52]:

$$|I_i| \leq |I_i^{rated}|, \quad (12)$$

where I_i^{rated} is the rated current of the i th line.

Discrete inequality constraints for STATCOM size and power factor are also satisfied as shown in Eqs. (13) and (14) [52]:

$$S_{min}^{Stat} \leq S_i^{Stat} \leq S_{max}^{Stat}, \quad (13)$$

$$pf_{min}^{Stat} \leq pf_i^{Stat} \leq pf_{max}^{Stat}, \quad (14)$$

here, the practical concern about STATCOM size and Power Factor (PF) as discrete values is considered. In ICA, the initial population is assumed to be equal to 100, and 10 initial imperialists are provided in all test cases. According to [35], the assimilation coefficient, assimilation angle coefficient, and revolution rate are equal to 2, $\pi/4$, and 0.7, respectively.

Using DPL, a sensitivity analysis is performed to examine the dp/dq ratio of system buses. Buses 18 and 33 are determined as sensitive and weak buses, respectively. The sensitivity coefficients for Buses 18 and 33 are also 1.167126

and 1.125105, respectively. The STATCOM installation location is suggested in Buses 18 and 33. More optimization results are shown in Table 7.

Due to the distribution of the harmonic load, (23 and 25) orders of HD_v at Bus 14 are increased by more than 3%, indicating a harmonic problem in the system. The other buses are within the allowable harmonic range. Considering the STATCOM, the voltage profile is improved, but harmonic issues can still be perceived at Buses 14 and 13, as shown in Figure 6(a). Figure 6(b) shows that the THD_v of Buses 13-15 has exceeded 5%. However, the harmonic level in some buses is decreased with the presence of the STATCOM. The bus voltage is also improved.

By comparing the system in modes S2 and S3, it is clear that in mode S3, with the presence of the STATCOM, line losses are reduced, and bus voltages are improved. This is shown in Figures 7 and 8.

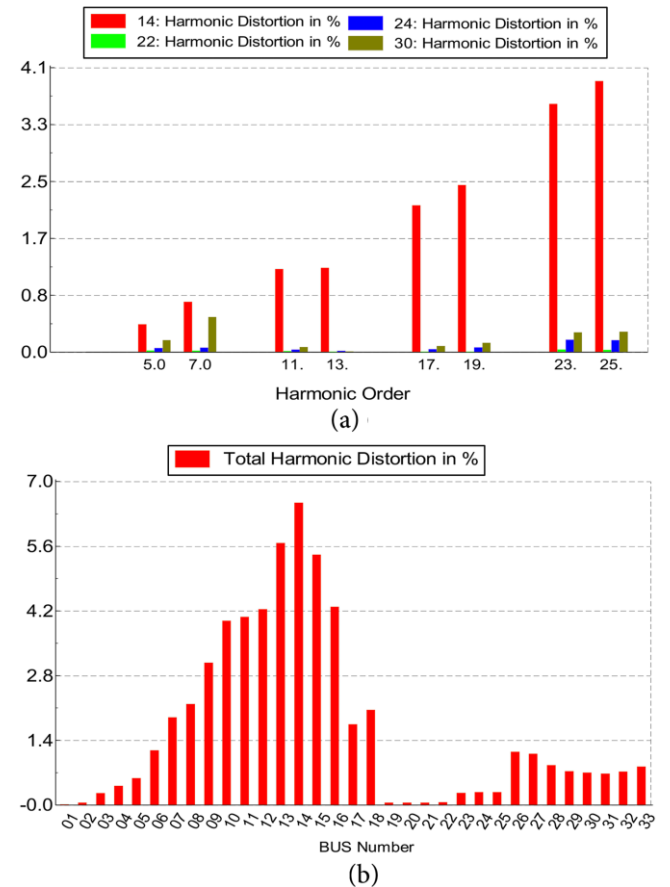
**Figure 6.** (a) HD_v of 5 to 25 at Buses 14, 22, 24, 30 and (b) THD_v of buses with STATCOM.

Table 7. Installation decisions.

STATCOM (location)			Passive filter (location)		
Bus number	18	33	Bus number	14	24
Size in MVar	1	1	Output reactive	1	0.7
Power MVar order			5	5	

Table 8. Results of examining the stability and power quality of the IEEE 33-bus system without a controller.

States of system	Voltage of buses (p.u.)	Stability of steady state and transient	THD _v (%)
Normal conditions	$V_{bus} > 0.95$	Stable	Permitted range $THD_v < 5$
With presence of a non-linear load without STATCOM and Filter	Some buses less than 0.95	Stable	Unallowable rang $THD_v > 5$
With presence of STATCOM and non-linear load	$1.05 < V_{bus} > 0.95$	Stable	THD_v should be checked. For 33 Bus $THD_v > 5$
With presence of Filter and non-linear load	$1.05 < V_{bus} > 0.95$	Stable	$THD_v < 5$
With presence of STATCOM (or Filter) and without non-linear load	$V_{bus} > 0.95$	Stable	$THD_v < 5$

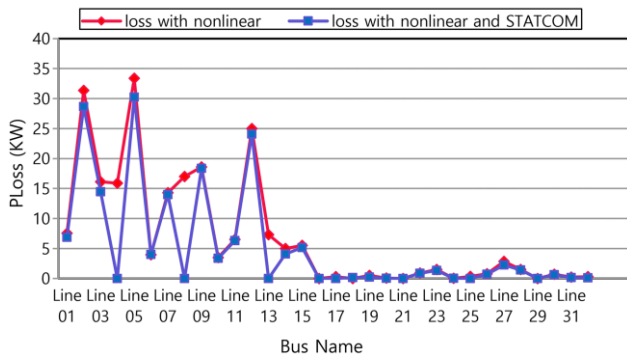


Figure 7. Lines' loss with STATCOM.

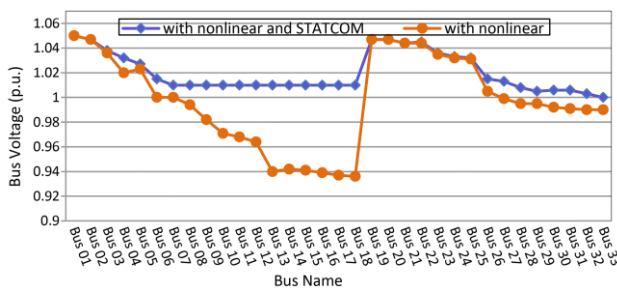


Figure 8. Buses' voltage with non-linear and STATCOM.

5.1.3. Evaluating the power quality with a non-linear load and filter in the network without a controller

In this case study, S5 is examined. As explained in the previous section, ICA assigns a filter for voltage stability and reduces losses and THD_v due to its high speed and accuracy. The sensitivity coefficients of Buses 14 and 24 are 1.135105 and 1.14056. Also, the maximum allowed value of the THD_v range is 5%. The filter installation location is suggested at Buses 14 and 24 with reactive power of 1 and 0.7 MVar. More optimization results are shown in Table 7. Also,

according to the frequency response result in Subsection 5.2, the filter is designed for the harmonic order 5. Figure 9 shows that the filter has considerably improved the harmonic level and the system's voltage.

5.1.4. Evaluating the power quality without a non-linear load and with the filter and STATCOM in the network without the controller

S6, S7, and S8, as other discrete states of the system, are examined in this section. In S6, S7, and S8, there is no non-linear load or harmonic issue in the network. The voltage profile is also controlled using a filter and STATCOM. The system eigenvalues are obtained by applying Modal calculations. In previous sections, all seven roots are presented in Table 6. Table 8 provides the results of analyzing the system's stability and power quality.

5.2. Power quality improvement using HAPQ for IEEE 33-bus distribution system with controller from the Sm scenario

After simulation for a 40 sec time horizon, non-linear loads were applied to Buses 14, 22, and 24 from 10 to 20 sec. The voltage changes in Buses 14 and 24 are shown in Figure 10. The buses' voltage decreased when non-linear loads were imposed on Buses 14 and 24. After 20 sec, all buses' voltages are improved using the proposed method.

Due to distributing the harmonic load, harmonic orders of HD_v at all buses are decreased by less than 3%, which indicates no harmonic issue in the system. The filter and STATCOM in the harmonic network effectively improve the HD_v, as shown in Figure 11(a). As depicted in Figure 11(b), the THD_v of all buses is less than 5% within the allowable bound. The harmonics of all buses are decreased with the filter and STATCOM. Regarding Figure 12(a), the network bus voltage is also improved.

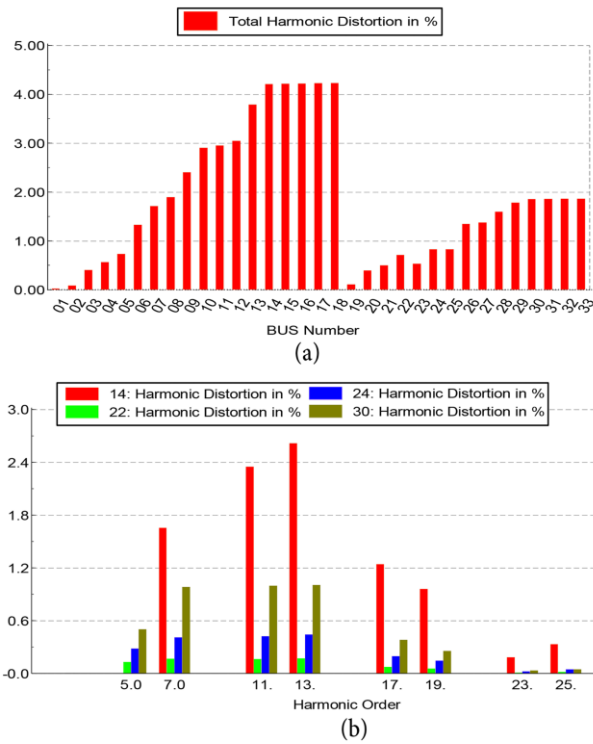


Figure 9. (a), HD_v of 5 to 25 at Buses 14, 22, 24, 30 and (b), THD_v of buses with filter.

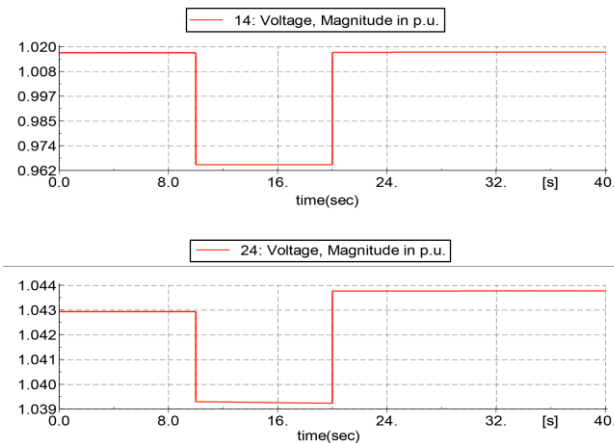


Figure10. Voltage changes at Buses 14 and 24 with Sm (NL Load, stat, filter) scenario and HAPQ controller.

According to Subsections 5.1.2 and 5.1.3, ICA is employed to locate the filter and STATCOM in the power grid. More optimization results are shown in Table 7. Also, according to the frequency response result in Figure 12(b), the filter is designed by the harmonic order 5.

Here, system eigenvalues are obtained by performing Modal calculations to analyze the system's stability under non-linear load. Seven roots are located on the left side of the $j\omega$ axis, and the system remains stable. Therefore, the system will not observe the harmonic problem with the presence of non-linear load, filter, and STATCOM. The voltage of buses is also improved, and the system remains stable. According to the results of the controller simulation using HAPQ, power quality indicators are improved, and the system is stable in the transient state. Referring to Theorem 1 in [46] about the stability of switched systems, if some subsystems

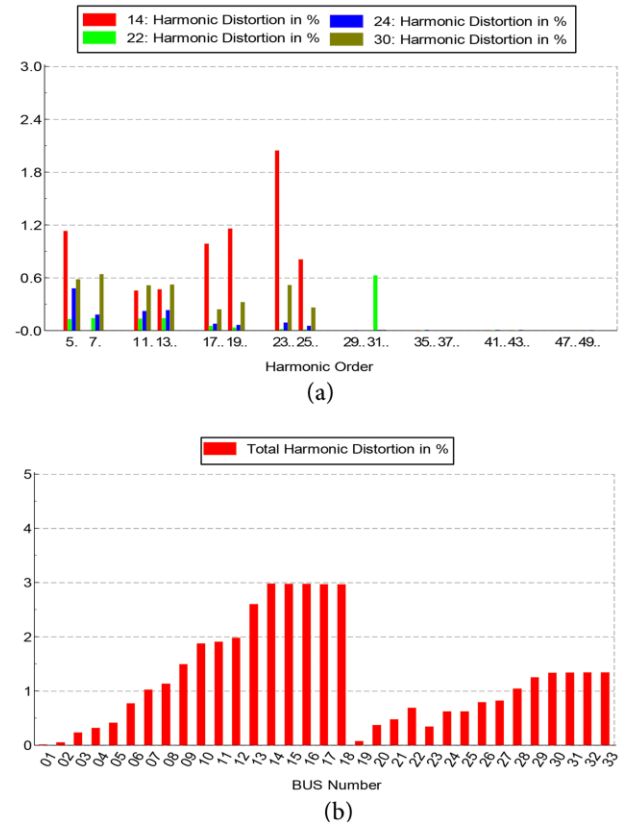


Figure11. (a) HD_v 5 to 49 at Buses 24, 22, 14, 30; and (b) THD_v of buses with Sm(NL Load, stat, filter) scenario and HAPQ controller.

are stable and some may be unstable; the time that the system ran in stable modes could be longer than the time taken in unstable modes to make the whole system stable. It depended on the growth and decline rates of the system in stable and unstable modes [46,47]. Based on the abovementioned theorem, the whole system is stable. The proposed HAPQ methodology is compared with other methods under the same experimental conditions. The HAPQ achieved a minimum voltage level compared to other heuristic methods, as shown in Figures 13(a) and (b). The HAPQ has enhanced the voltage profile at all load levels. The optimal value of the decision parameter can improve the system's performance. Table 9 shows that Particle Swarm Optimization (PSO) [24], Modified Group-experience of Teaching Learning Based Optimization (MG-TLBO) [23], and the proposed HAPQ have reduced THD_v by less than 5% with improved voltage profiles for all load levels. Moreover, the maximum THD_v reduction is achieved for the proposed method compared to PSO [25] and MG-TLBO [23].

By investigating the results of other optimization algorithms such as Genetic Algorithm-based approach (GA-based) [28], Artificial Bee Colony (ABC) [30], Biogeography-Based Optimisation (BBO) [31], Backtracking Search Algorithm (BSA) [32], Gravitational Search Algorithm (GSA) [33], Grey Wolf Optimiser (GWO) [34], ICA [35], Wind Driven Optimisation (WDO) [36] and Genetic Algorithm- Particle Swarm Optimization (GA-PSO) [37], it is found that the HAPQ provides effective, robust and high-quality solutions. Figure 14 demonstrates the comparison of maximum THD_v for multifarious algorithms. The proposed HAPQ improved the voltage profile and harmonics better than other methods.

Table 9. System performance of harmonics populated.

Cases	Load level	THD _{vmax} (%)	V _{min} (p.u.)
Without controller	Light	6.0883	0.9583
	Nominal	13.3889	0.9131
	Peak	24.4528	0.8528
PSO [24]	Light	1.4300	0.9914
	Nominal	2.659	0.9821
	Peak	3.0681	0.9658
MG-TLBO [23]	Light	1.7334	0.9921
	Nominal	2.3229	0.9816
	Peak	3.2841	0.9706
HAPQ	Light	1.3983	1.0034
	Nominal	2.2270	1.0001
	Peak	3.0001	0.9899

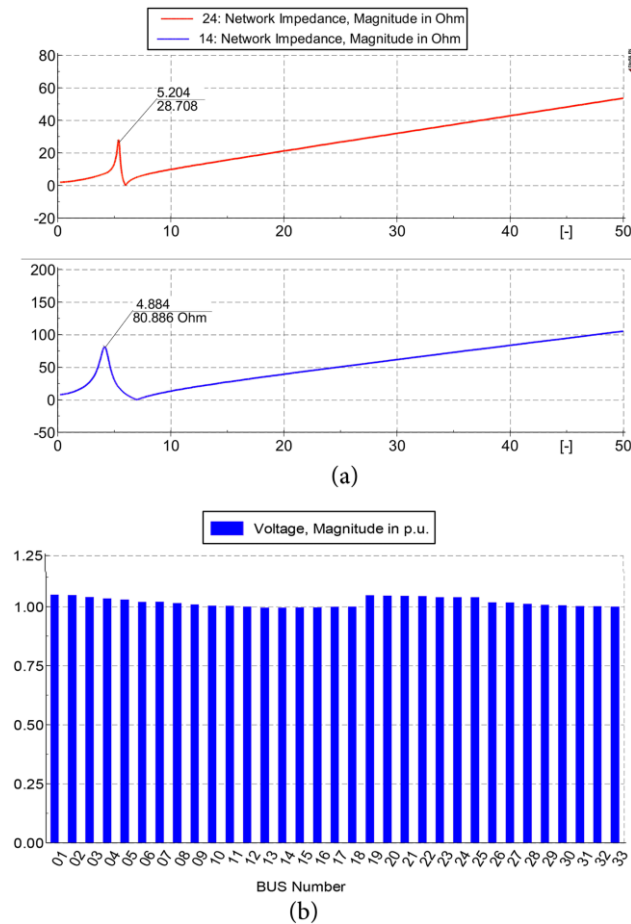


Figure12. (a) The voltage of buses; and (b) system frequency response at Buses 14 and 24 with Sm (NL Load, stat, filter) scenario and HAPQ controller.

6. Simulation results for the second case study

SKED1 test system with real data is located in a rural area in Kerman province, Iran [38]. Figure 15 presents a 20kV power distribution system with terminals and a feeder (Feeder 1) with lateral branches. The total peak load of the system mentioned above is 6.16 MW.

6.1. Evaluating steady-state power quality for the discrete states without a controller

6.1.1. Studying the power quality with a non-linear load in the network without the controller

In this case, S2 is investigated as a discrete mode, and the harmonic issue for voltage, current, and voltage profiles is

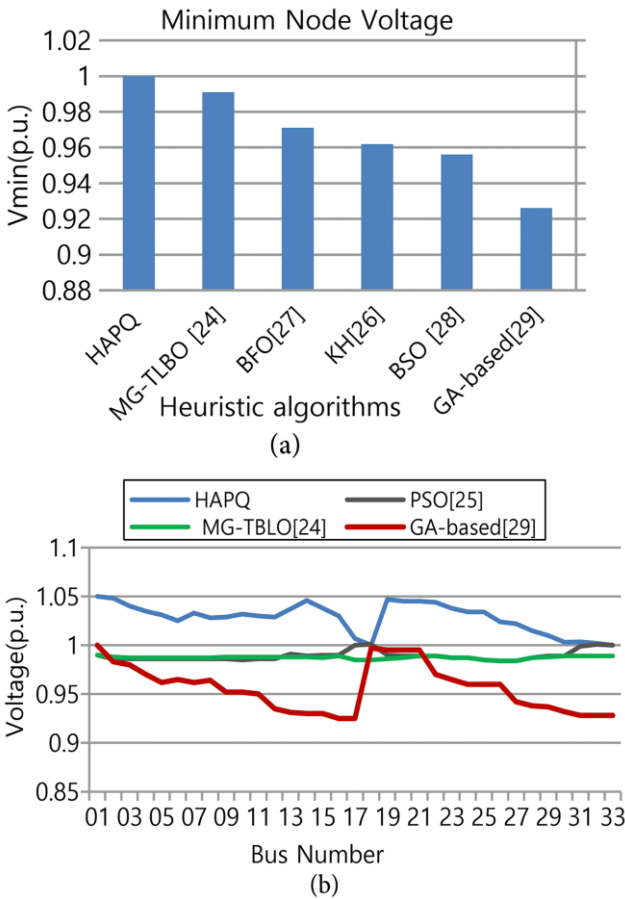


Figure 13. (a) Comparison of the minimum voltage in heuristic methods; and (b) voltage profile comparison for multifarious algorithms for IEEE 33-bus system.

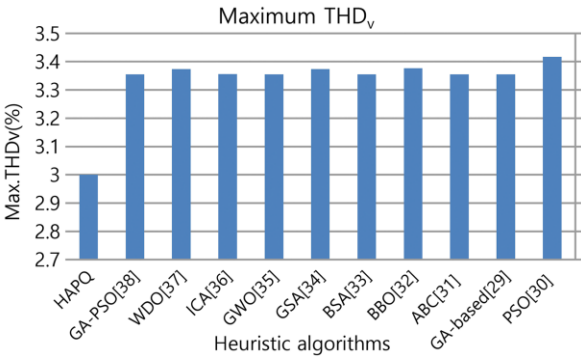


Figure 14. Comparison of maximum THD_v for IEEE 33-bus system.

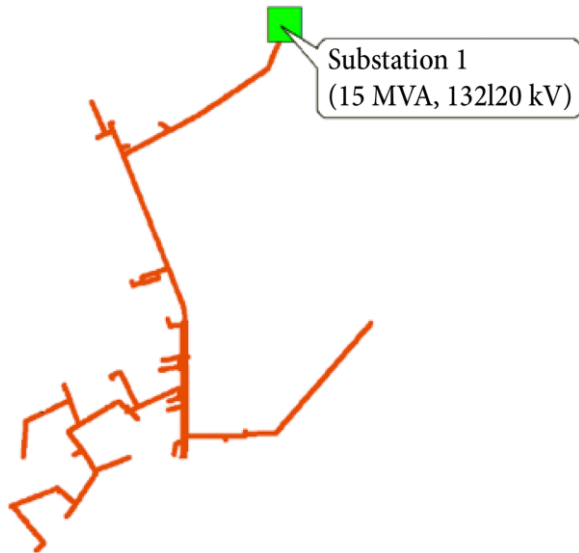


Figure 15. A part of feeder 1 in a real distribution test system (SKED1) [39].

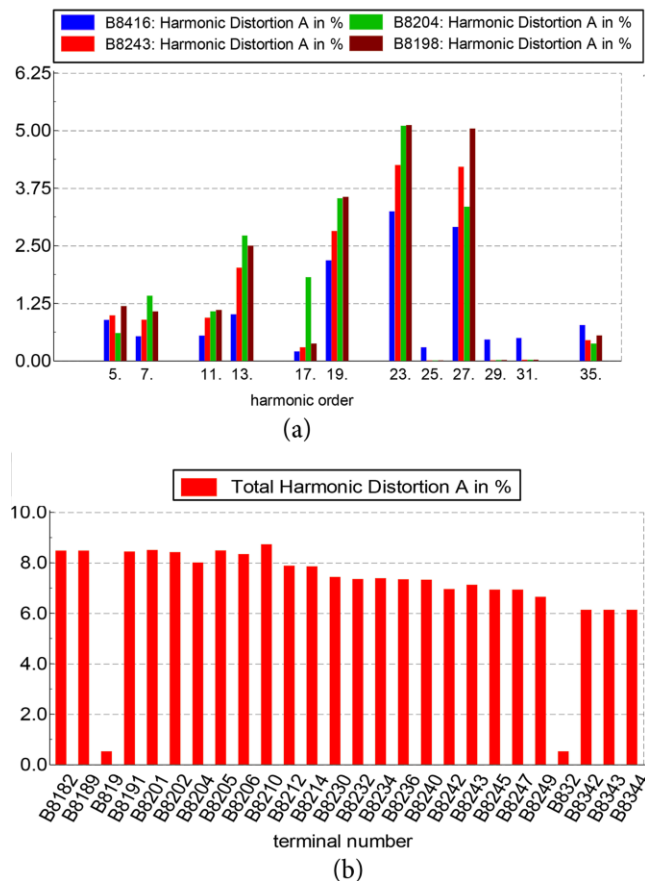


Figure 16. (a) HD_v 5 to 35 at terminals B8416, B8198, B8243, B8204; and (b) THD_v of terminals with non-linear load.

perused. The installation location and percentage of non-linear loads are presented in Table 10. This case study illustrates the harmonic spectrum, as shown in Table 5 [23]. By implementing the harmonic load flow, HD_v of 19, 23, and 27 at the above-mentioned terminals increased by more than 3%, which indicates a harmonic problem. HD_v for other terminals is within the allowable harmonic range, as shown in Figure 16(a). According to Figure 16(b), the THD_v of terminals is above 5%. There is a voltage drop issue at several terminals.

Table 10. Non-linear loads for SKED

Terminal No.	Non-linear load type	Percentage (%)
B8243, B8198	Fluorescent	43
B8416	PC Workstation	29
B8204	ASD	65

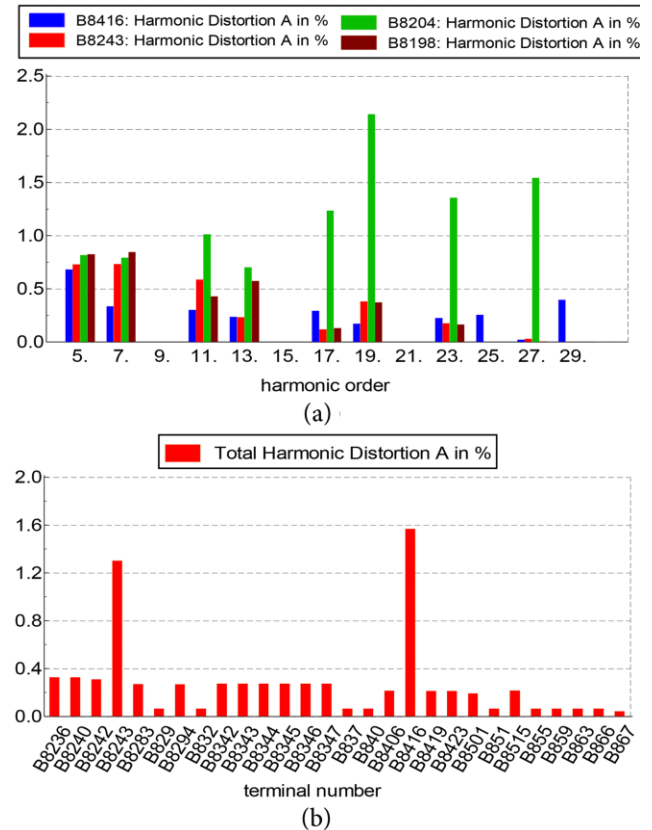


Figure 17. (a) HD_v 5 to 29 at terminals B8416, B8198, B8243, B8204; and (b) THD_v of terminals with STATCOM

6.1.2. Studying the power quality with a non-linear load and STATCOM in the network without the controller

In this section, S3 is examined as another discrete state. ICA is employed to locate the STATCOM for voltage stability and reducing losses. ICA also determines the optimal filter placement and size to reduce the total system losses. Using DPL, a sensitivity analysis is performed to examine the dp/dq ratio of system terminals. Terminals B878 and B1012 are determined as sensitive and weak buses, respectively. The sensitivity coefficients for terminals B878 and B1012 are also 1.1618 and 1.1464, respectively. The STATCOM installation location is suggested at terminals B878 and B1012. More optimization results are shown in Table 11.

After distributing the harmonic load, the HD_v order at the terminals is less than 3%, which indicates no harmonic issue in the system. The voltage is considerably improved considering STATCOM, and there is no harmonic problem at terminals, as shown in Figure 17(a). According to Figure 17(b), it is clear that the THD_v of terminals is less than 5% in the permissible range. It is also evident that with the presence of STATCOM, the harmonics of all terminals have decreased. The network terminal voltage is improved.

Table 11. Installation decisions for SKED.

STATCOM (location)			Passive filter (location)		
Terminal number	B878	B1012	Terminal number	B3752	B926
Size in MVar	0.5	0.5	Output reactive	1	1
			Power MVar	5	5

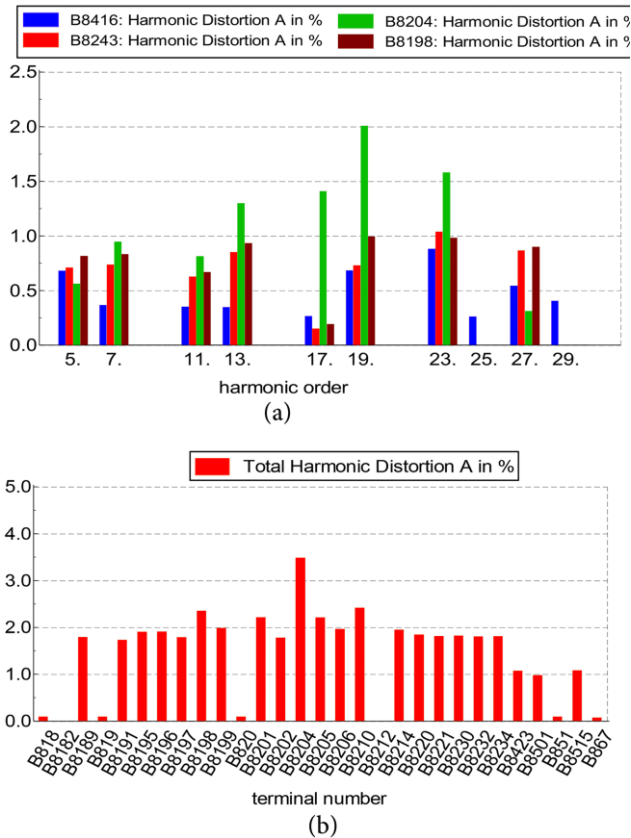


Figure 18. (a) HD_v 5 to 29 at terminals B8416, B8243, B8204, B8198 and (b) THD_v of terminals with filter

6.1.3. Studying the power quality with a non-linear load and filter in the network without the controller

S5 is examined in this section for the SKED1 test system. ICA is again employed to locate a filter. Terminals B3752 and B926 are determined as sensitive and weak buses, respectively. The sensitivity coefficients for terminals B3752 and B926 are also 1.04639 and 1.09780, respectively. The filter placement is suggested at terminals B3752 and B926 with two dual-stage capacities of 1 Mvar. According to Figure 18(a) and (b), it can be found that the filter has improved the harmonic issue and the voltage of the system.

6.1.4. Studying the power quality without a non-linear load and with a filter and STATCOM in the network without the controller

S6, S7, and S8 have been evaluated in this subsection. The voltage profile is controlled using a filter and STATCOM in these cases. The system eigenvalues are obtained with Modal calculations to analyze the system stability. The results of analyzing the stability and power quality of the system are given, similar to Table 8.

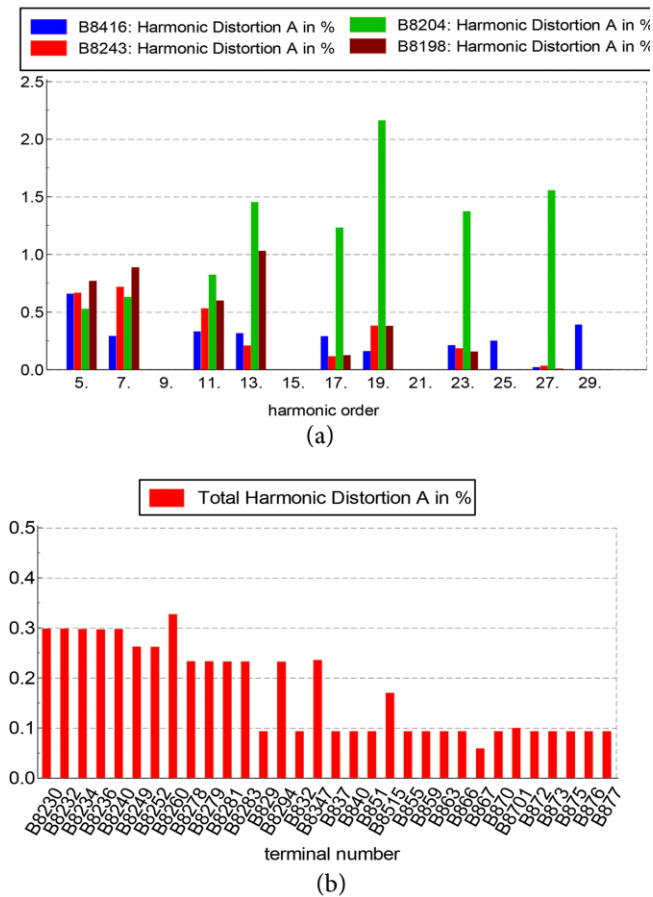


Figure 19. (a) HD_v 5 to 29 at terminals B8416, B8243, B8204, B8198; and (b) THD_v of terminals with Sm (NL Load, stat, filter) scenario and HAPQ controller.

6.2. Power quality improvement using HAPQ controller for SKED1 test system for the Sm scenario

According to Sections 2 and 3, ICA is employed to locate the filter and STATCOM in the power grid. More optimization results are shown in Table 11. After distributing the harmonic load, the HD_v of 5, 11, 17, and 19 in all terminals are decreased by less than 3% as shown in Figure 19(a). As demonstrated in Figure 19(b), the THD_v of all terminals is less than 5% within the allowable range. By considering the filter and STATCOM, the network voltage is improved effectively, as shown in Figure 20(a). In order to analyze the system's stability in the presence of non-linear loads, system eigenvalues are obtained, where all roots are located on the left side of the $j\omega$ axis, as presented in Figure 20(b). Therefore, it can be concluded that the system has no harmonic issue considering the non-linear load, filter, and STATCOM. The voltage of the network terminals is also improved, and the system remains stable. According to the

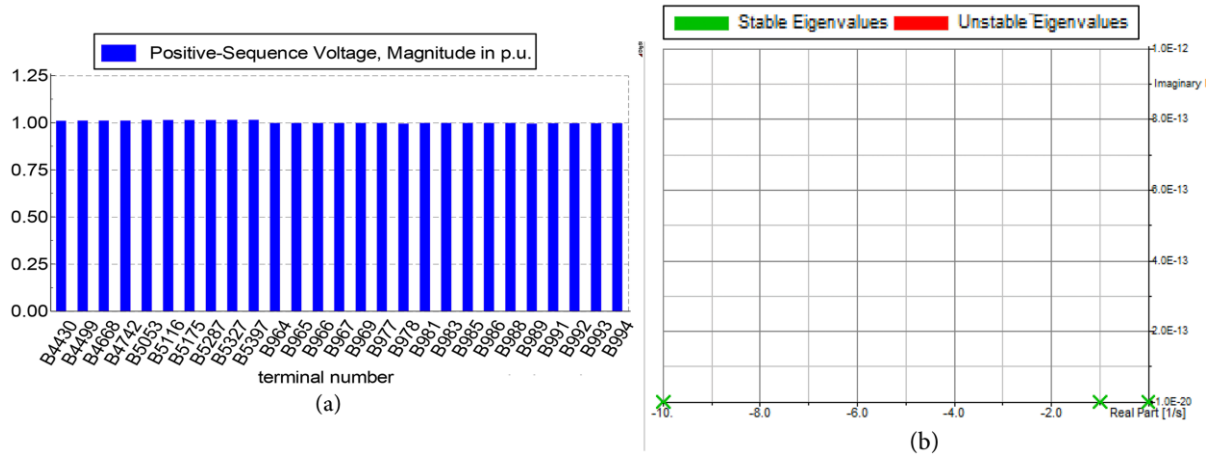


Figure 20. (a) The voltage of terminals; and (b) eigenvalue plot of system with Sm (NL Load, stat, filter) scenario and HAPQ controller.

results of the controller simulation using the HAPQ, power quality indicators are improved, and the system is still stable in the transient state. Based on Theorem 1 in [46], can be mentioned that the whole system is stable.

7. Conclusions

In this paper, a new method called Hybrid Automata in Power Quality (HAPQ) is proposed to control and improve stability and power quality. In order to achieve better power quality, a model is introduced for optimal controller use, and the general behavior of the power system is presented with HAPQ. Hybrid Automata (HA) incorporates continuous dynamics as well as discrete switching behavior into the modeling and control framework. Discrete states are considered as a combination of discrete events, including the presence and absence of the Static Compensator (STATCOM), filters, and disturbances resulting from a non-linear load. The system without a controller, overall behavior is examined in eight different 8 modes with specific continuous dynamics. Then, power quality and voltage stability are evaluated using multifarious approaches such as Distortion of Voltage (THD_v), bus and terminals' voltage and system eigenvalues. The simulation results emphasized that THD_v can be considerably reduced by HAPQ. Moreover, the power quality is improved by considering STATCOM and filters in distribution networks. After applying the supervisory controller, the numerical results revealed that the controller with HAPQ performs appropriately on control targets and brings THD_v and the voltage of buses and terminals into the permissible range. The system is stable. Also, the proposed HAPQ approach can be easily applied to other power systems as well.

Acknowledgment

The authors would like to appreciate the South of Kerman Electric Power Distribution Company and its expert personnel.

Appendix A

For example, in the IEEE 33-bus system, achieve matrix A_1 by using the system eigenvalues $p_1(s)$ can be formulated as follows:

$$P_1(s) = s^2 \times (s+1)^2 \times (s+10)^2 \times (s+0.00012). \quad (A.1)$$

As a consequence of simplifying the $P_1(s)$ coefficients, it can be rewritten as follows:

$$P_1(s) = s^7 + a_6 s^6 + \dots + a_1 s + a_0. \quad (A.2)$$

Coefficients $a_1, a_2, \dots, a_6$ can be presented as Eq. (A.3):

$$A_1 = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \dots & 1 \\ -a_0 & -a_1 & -a_2 & \dots & -a_6 \end{bmatrix} \quad (A.3)$$

It is possible to determine the matrices of $A_{17 \times 7}$ for the other seven states, i.e., using a similar approach.

Abbreviations

HAPQ	Hybrid Automata in Power Quality
PSO [24], [29]	Particle Swarm Optimization
MG-TLBO [23]	Modified Group-experience of Teaching Learning Based Optimization
KH [25]	Krill Herd
BFO [26]	Bacterial Foraging Optimization
BSO [27]	Backtracking Search Optimization
GA-based [28]	Genetic Algorithm-based approach
ABC [30]	Artificial Bee Colony
BBO [31]	Biogeography-Based Optimisation
BSA [32]	Backtracking Search Algorithm
GSA [33]	Gravitational Search Algorithm
GWO [34]	Grey Wolf Optimiser
ICA [35]	Imperialist Competitive Algorithm
WDO [36]	Wind Driven Optimisation
GA-PSO [37]	Genetic Algorithm- Particle Swarm Optimization

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

All authors contributed to the reported work for conceptualization, methodology, validation, writing-review and editing, and supervision.

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