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

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Abstract

This paper proposes a systematic approach to the design of a supervisory control scheme using a new method of the Hybrid Automata in Power Quality (HAPQ) improvement. In order to access a better power quality, a model is introduced for optimal controller uses and the general behavior of the power system is presented with Hybrid Automata (HA). The formalism of a hybrid system contains continuous dynamic 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. Discrete Event Systems (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.

Keywords: DES, HAPQ, THD_v, HA Modeling, Supervisory controller.

1. Introduction

In distribution network, unbalance distributed generation, increasing non-linear loads, and single-phase/unbalanced loads leads to power quality challenges [1]. The extensive use of power electronics based equipment and non-linear loads at point of common coupling (PCC), generates harmonic currents deteriorating the quality of the electric power. Moreover, from the system operator's viewpoint, excessive higher harmonic level is 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 diod (LED), adjustable speed drives (ASD) fridge, 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) reaches 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 equipment have been used to improve power quality. The static compensators (STATCOMs) that their structures are similar to active power filters can be used to compensate harmonics. Also, STATCOM can supply reactive power and can be used to compensate harmonics but the effect of STATCOM presence to reduce harmonics should be investigated.

In recent years, many research has addressed the issue of improving power quality. Custom power devices are suggested as one of the best solutions to improve the power 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 in 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 load, 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 Synchronous Compensator (D-STATCOM) is a shunt compensator in the distribution systems that one of the most important tasks is to improve the imbalance, reduce, and eliminate the harmonic 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 other ones 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 [15,16].

Hybrid systems are dynamic systems interacting with continuous and discrete-valued states [17]. Hybrid system reachability is widely deployed for verification of system safety properties whose behaviors are represented by a hybrid system mathematical model [17–19]. Power system dynamics and control is contained hybrid nature [20]. [20] 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 [21].

In [22], a systematic approach for designing and analyzing a supervisory control scheme in power systems using the 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 [22], a power system HA model is employed as a DES plant and controller. Also, the discrete events used in [23], in addition to [22], 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 distributed generation (DG) [23].

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 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 power quality and stability straightforward 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. In this paper, first, a scenario of Sm(NLLoad, Stat, Filter) is defined for various system modes. The controller is designed by HA modelling under disturbance resulting from a Nonlinear Load (NLLoad). 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 [24–38].

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 south of Kerman Electrical Distribution (SKED1) test system with actual data [39]. 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 using 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 system modes 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 system mode change is based on differential equations where the modes vary over time. In event-driven and DES systems, the changes in the system mode depends on the occurred events [40,41].

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 [41].

2.1. Hybrid Automata

In this paper, the HA method is utilized to model the system. The main purpose of a physical process mathematical modeling is to make the problem understandable for designing the controller. HA can be expressed as shown in Equation 1 [41].

$$H = (Q, v, f, Init, Inv, \theta, G, R) \tag{1}$$

-Q is a limited set of system discrete modes; $Q = \{q_1, ..., q_k\}$, $q \in Q$.

-V 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 $(q, x) \in Q \times v$;

-$Init \subseteq Q \times R^n$ is a set of the system’s initial modes and conditions;

-$Inv : Q \to 2^{R^n}$ is the description for the locations characteristics. It is a prerequisite for staying in or passing 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.

-$G : \theta \to 2^{R^n}$ is the system guard prerequisite, which is applied to the arcs of HA model. It constrains the continuous dynamics' function.

-$R : \varepsilon \to 2^{R^n} \times 2^{R^n}$ 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 [41].

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 system modes 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:

a) THD_v and harmonic distortion of the busses [42].
b) The voltage of the busses [43], [44] and [45].
c) The eigenvalues of a system [43], [44] and [46].
d) The stability theory of the switched systems [47,48]. *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 most sensitive buses. The standard bus voltage deviation is ±5%. It means that a voltage $1.05 < V_{bus} > 0.95$ is standard and permitted [2,43,49].

ii) The current of sensitive load with STATCOM and filter: The control of $\mathrm{THD_v}$ is adjusted to the $\mathrm{THD_v}$ of the bus, while the standard $\mathrm{THD_v}$ deviation in each bus is less than 5% [24]. If the power system is subjected to a non-linear load and the $\mathrm{THD_v}$ is exceeded from the allowable limit, the STATCOM is applied. According to Flowchart of the proposed HAPQ controller Figure 1.(B), $\mathrm{THD_v}$ 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 to reduce $\mathrm{THD_v}$ should be investigated.

If the $\mathrm{THD_v}$ 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 disturbance of non-linear load and power quality control elements such as STATCOM and filter as shown in Table 1. According to the events value 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 the "m" expressed the mode number. Table 2 presents the abovementioned 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 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 connected to the system, the system mode changes from S1 to S2 and $\mathrm{THD_v}$ index rises above the allowable range of 5%. In order to handle the harmonic issue, the STATCOM first enters and the system status modifies to S3. If $\mathrm{THD_v}$ index is not still within the allowable range, a filter is called and the system is included in S4. The transitions between 8 states are comprehensively shown in Figure 2.

The HA model of the system is formulates as shown in Equation 1 [41]:

Q is a set of discrete states as shown in Equation 2:

$$Q \in \{S1, S2, S3, S4, S5, S6, S7, S8\} \tag{2}$$

v is the system continuous variables set and defined in Digsilent Power Factory software as shown in Equation 3 [50]:

$$v \in \{phi, speed, psie, psiD, psiX, psiQ\} \tag{3}$$

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

The continuous dynamics of the system is represented as $\dot{x} = A_i(x)$. In order to obtain A_i in Equation 4, given the eigenvalues corresponding to each state, the transfer function's denominator for the system is procured by Equation 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.

$$\mathrm{A}_i \in \{\mathrm{A}_1, \mathrm{A}_2, \mathrm{A}_3, \dots, \mathrm{A}_8\}, \quad i = 1, 2, .. \tag{4}$$

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

$$P_i(S) = S^n + a_{n-1}S^{n-1} + \dots + a_1 S + a_0 \tag{5}$$

Inv is expressed as shown in Equation 6:

$$\mathrm{Inv} \in \{NLLoad = 0, NLLoad = 1\} \tag{6}$$

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 Equation 7.

$$G \in \{NLLoad = 0, NLLoad = 1, Stat = 0, Stat = 1, Filter = 0, Filter = 1\} \tag{7}$$

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 [51]. The parameters of this standard 12.66 KV power distribution system with 33 buses and a feeder with four lateral branches are described in [52].

5.1. Evaluating Steady-State Power Quality for Discrete States without 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 Digsilent Power Factory software, and programming is executed using DPL code and content.

In S2, a non-linear load is incorporated into the test system. Filter and STATCOM are not considered, and the harmonic issue 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 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 of bus 10 to bus 13 is above 5%, as shown in Figure 5(b). There is a voltage drop problem on 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 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 [53]. The first term of the objective function (F1) is related to the reduction of power losses, defined as Equation 8. The second term of the objective function (F2) is related to the reduction of THD_v, defined as Equation 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 Equation 8.

$$F_1 = Min \sum_{i=0}^{n} (I_i)^2 .r_i \qquad F_2 = Min THD_v = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1} \times 100\% \qquad F_3 = Min\, SUM\,(abs(V_n - V_i)) \qquad for\ i = 2,3,...,N_B \tag{8}$$

Where v_n is 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 [53]:

$$P_{sys} + P_{Stat} = P_d + P_{loss} \tag{9}$$

$$Q_{sys} + Q_{Stat} = Q_d + Q_{loss} \tag{10}$$

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 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 Equation 11 [53]:

$$V_{\min} \le V_{sys}^{i} \le V_{\max} \tag{11}$$

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

The thermal capacity limits of the network's lines are considered as shown in Equation 12 [53]:

$$\left|I_i\right| \le \left|I_i^{rated}\right| \tag{12}$$

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

Discrete inequality constricts for STATCOM size and power factor are also satisfied as shown in Equation 13 and Equation 14 [53]:

$$S_{\min}^{Stat} \le S_i^{Stat} \le S_{\max}^{Stat} \tag{13}$$

$$pf_{\min}^{Stat} \le pf_i^{Stat} \le pf_{\max}^{Stat} \tag{14}$$

Here, the practical concern about STATCOM size and power factor (pf) as discrete values are 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 [36]**,** the assimilation coefficient, assimilation angle coefficient, and revolution rate are equal to 2, π/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 distributing the harmonic load, {23, and 25} orders of HD_v at bus 14 are increased by more than 3%, indicating the 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 apperceive 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 harmonics level in some buses is decreased with the presence of STATCOM. The bus voltage is also improved.

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

5.1.3. Evaluating the power quality with a non-linear load and filter in the network without 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 coefficient of buses 14 and 24 equal 1.135105 and 1.14056. Also, the maximum allowed value of the THD_v range is 5%. The filter installation location is suggested in buses 14 and 24 with reactive power 1 and 0.7 MVAr. More optimization results are shown in Table 7. Also, according to the frequency response result in section 5.2., the filter is designed by 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 non-linear load and with 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 emphasizes 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 filter and STATCOM. Regarding Figure 12(a), the network bus voltage is also improved.

According to sections 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 in 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 [47] about the stability of switched systems, if some subsystems are stable and some 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 [47,48]. Based on the abovementioned theorem, the whole system is stable. The proposed HAPQ methodology is compared with other methods with the same experimental conditions. The HAPQ achieved a minimum voltage level compared to other heuristic methods, as shown in Figures 13(a) and 13(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 presents that PSO [25], MG-TLBO [24], and 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 [24].

By investigating the results of other optimization algorithms such as GA-based [29], ABC [31], BBO [32], BSA [33], GSA [34], GWO [35], ICA [36], WDO [37] and GA-PSO [38], 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.

6. Simulation Results For The Second Case Study

SKED1 test system with real data is located in a rural area in Kerman province, Iran [39]. 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 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 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 [24]. By implementing the harmonic load flow, HD_v of 19, 23, and 27 at the abovementioned terminals are increased more than 3%, which indicates the 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.

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 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 in terminals B878 and B1012. More optimization results are shown in Table 11.

After distributing the harmonic load, the HD_v order at 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.

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 in terminals B3752 and B926 with two dual-stage capacities of 1 Mvar. According to Figure 18(a) and Figure 18(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 non-linear load and with 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.

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 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 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 [47], it can be mentioned that the whole system is stable.

7. Conclusions

In this paper, a new method called HAPQ is proposed to control and improve stability and power quality. In order to access a better power quality, a model is introduced for optimal controller uses and the general behavior of the power system is presented with HAPQ. 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 STATCOM, filter and disturbances resulting from a non-linear load. The system without controller, overall behavior is examined in different 8 modes with specific continuous dynamics. Then, power quality and voltage stability are evaluated using multifarious approaches such as THD_v, buses 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 filter in distribution networks. After applying the supervisory controller, the numerical results revealed that the controller with HAPQ appropriately performs on control targets and destines THD_v and voltage of buses and terminals in to the permissible range. The system is stable. Also, the proposed HAPQ approach can be easily applied to other power systems as well.

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Appendix A

For example in IEEE 33-bus system, achieve matrix A_1 by using the system eigenvalues, $P_1(S)$ can be formulated as Equation A.1:

$$P_1(S)=S^2*(S+1)^2*(S+10)^2*(S+0.00012) \tag{A.1}$$

As a consequence of simplifying the $P_1(S)$ coefficients, it can be rewritten as Equation A.2:

$$P_1(S)=S^7+a_6S^6+...+a_1S+a_0 \tag{A.2}$$

Coefficients $a_1, a_2, ..., a_6$ can be presented as Equation A.3:

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

It is possible to determine the matrixes of $A_{i\,7*7}$ for the other seven states, i.e. $A_2, A_3, ..., A_8$, using the similar approach.

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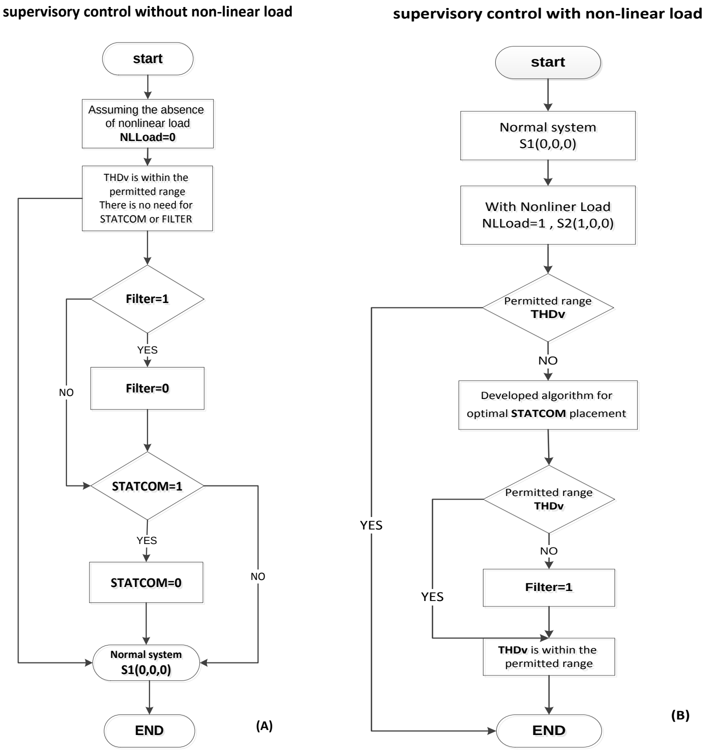
Abbreviations used in Tables and Figures

Abbreviation	Explanation	Abbreviation	Explanation
HAPQ	Hybrid Automata in Power Quality	BBO [32]	Biogeography-Based Optimisation
PSO [25], [30]	Particle Swarm Optimization	BSA [33]	Backtracking Search Algorithm
MG-TLBO [24]	Modified Group-experience of Teaching Learning Based Optimization	GSA [34]	Gravitational Search Algorithm
KH [26]	krill herd	GWO [35]	Grey Wolf Optimiser
BFO [27]	Bacterial Foraging Optimization	ICA [36]	Imperialist Competitive Algorithm
BSO [28]	Backtracking Search Optimization	WDO [37]	Wind Driven Optimisation

GA-based [29]	Genetic Algorithm-based approach	GA-PSO [38]	Genetic Algorithm- Particle Swarm Optimization
ABC [31]	Artificial Bee Colony		

Figures:



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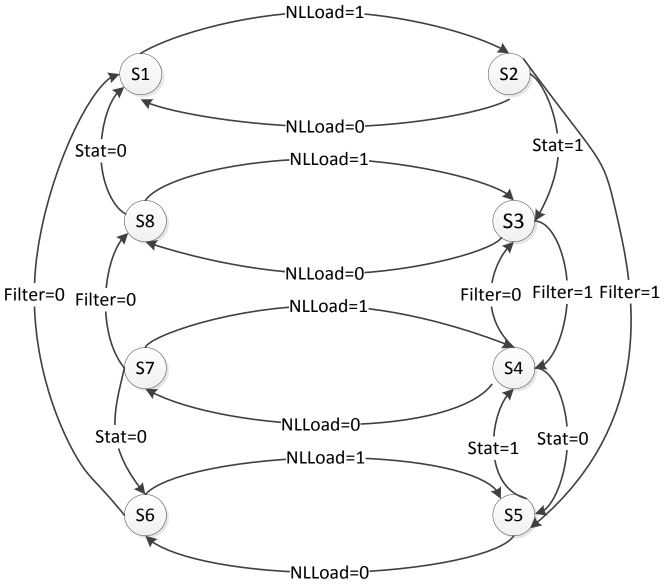

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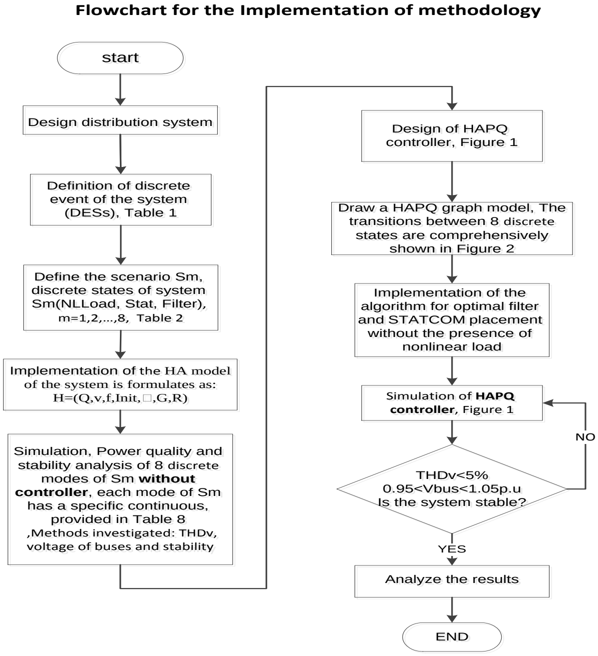

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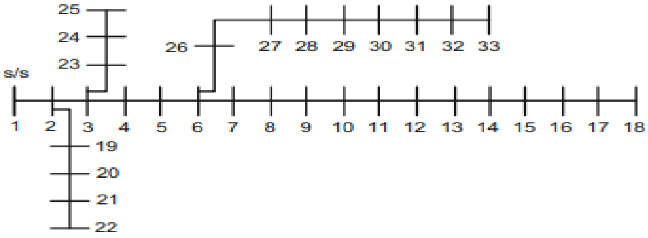

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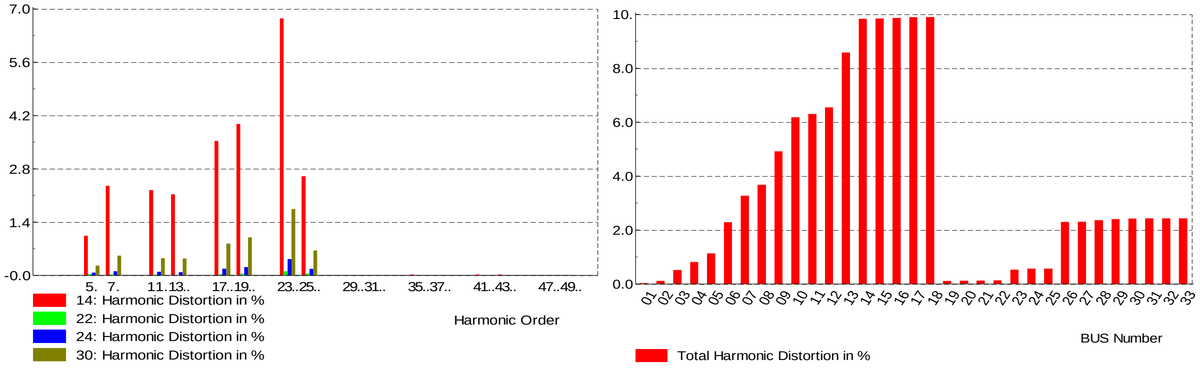

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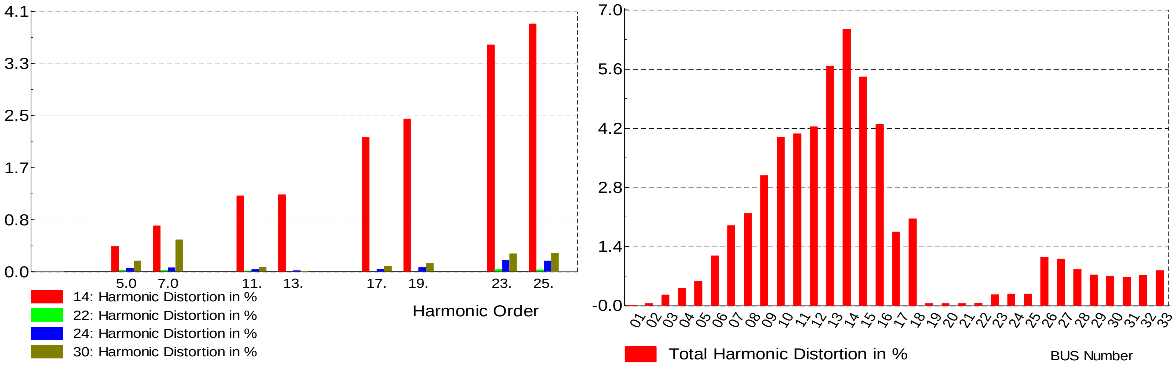

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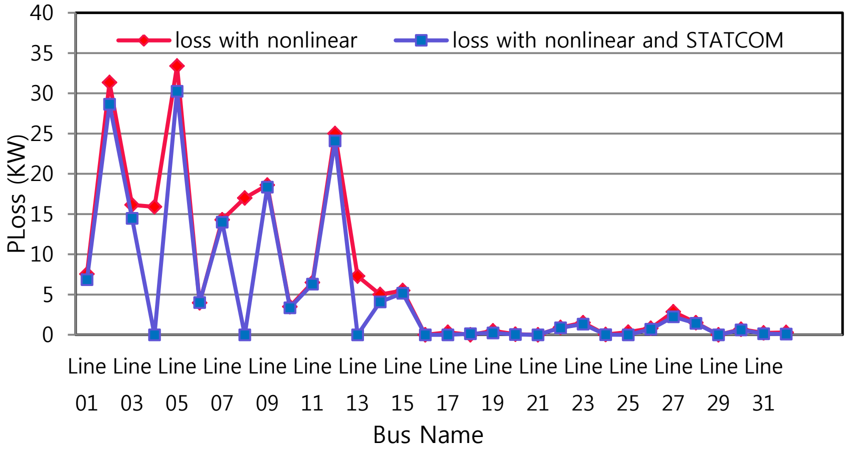

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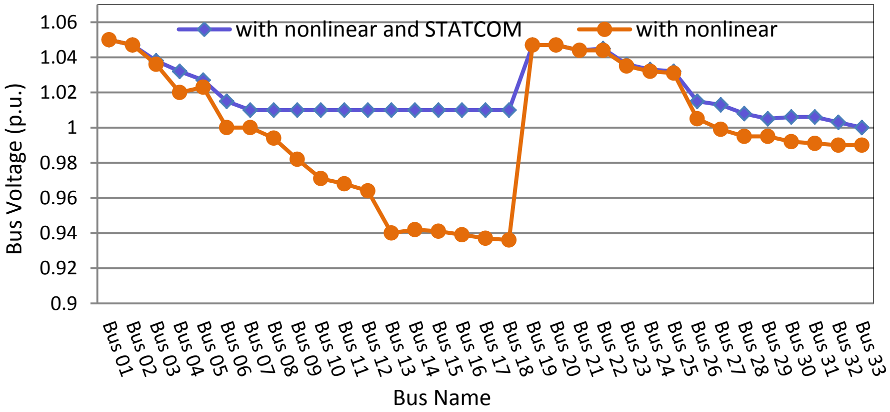

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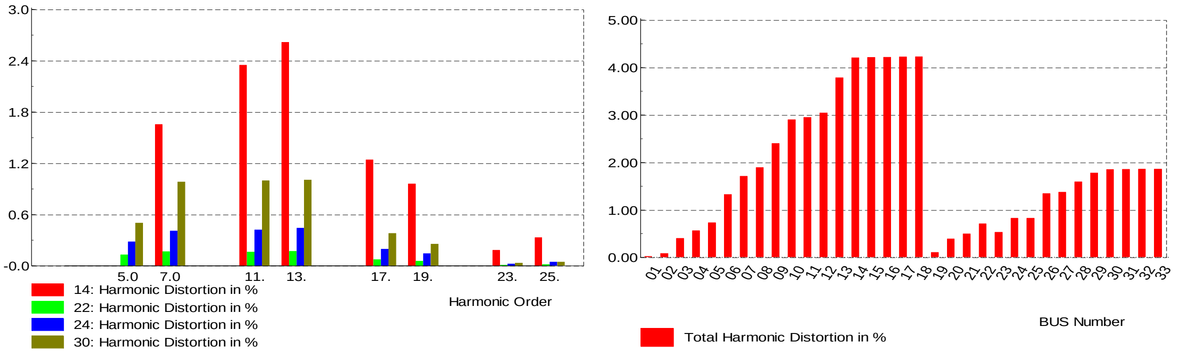

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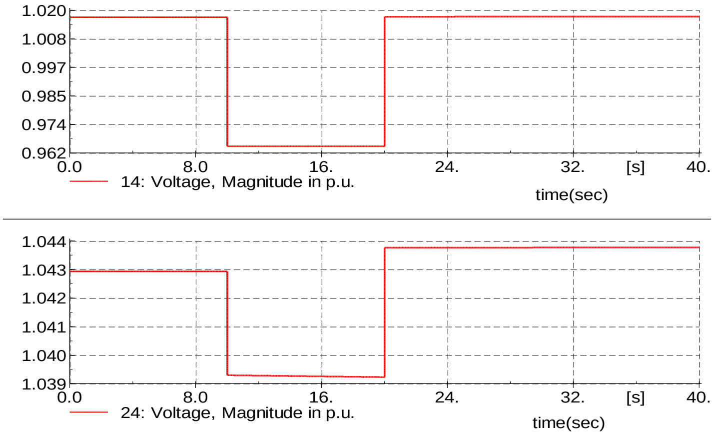

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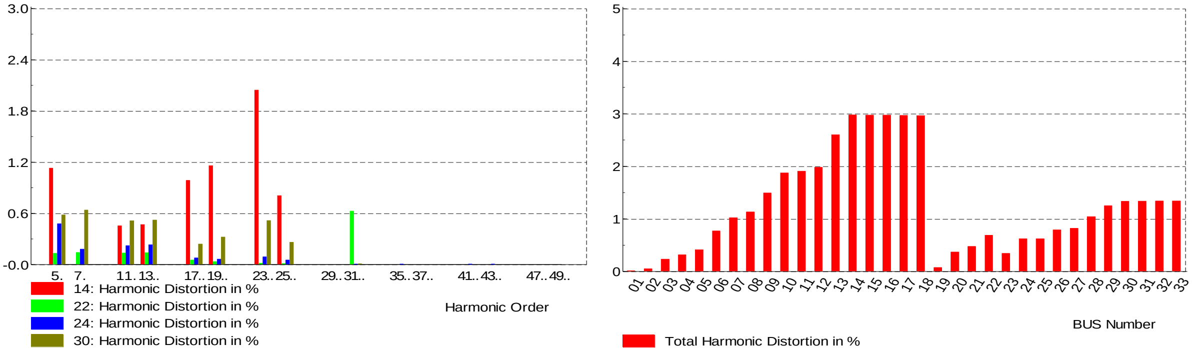

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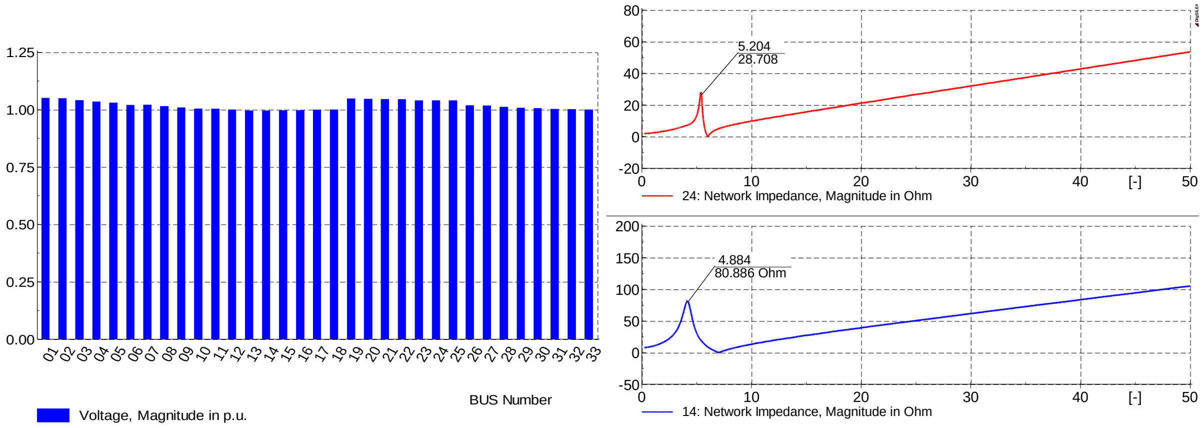

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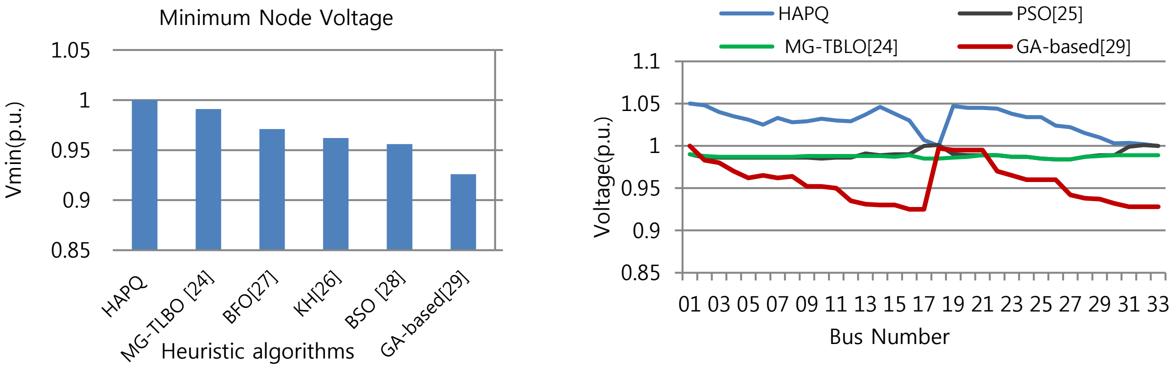

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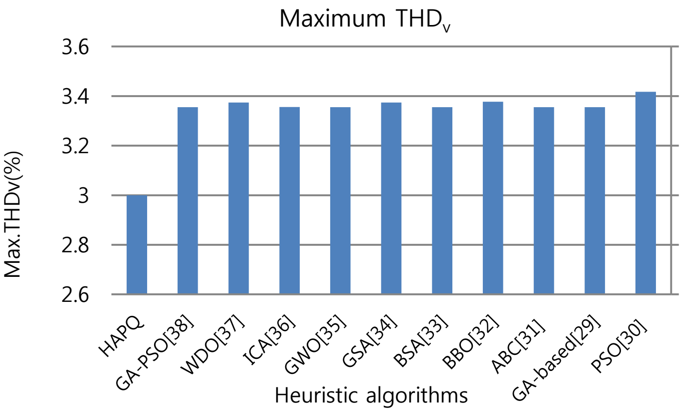

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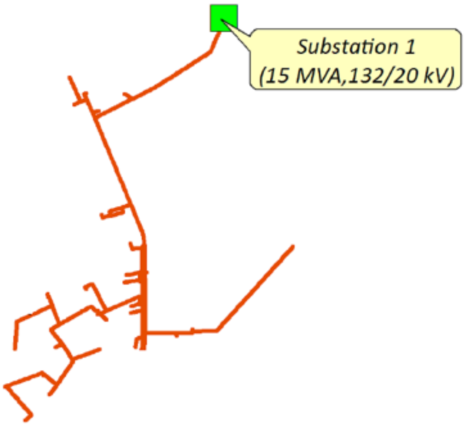

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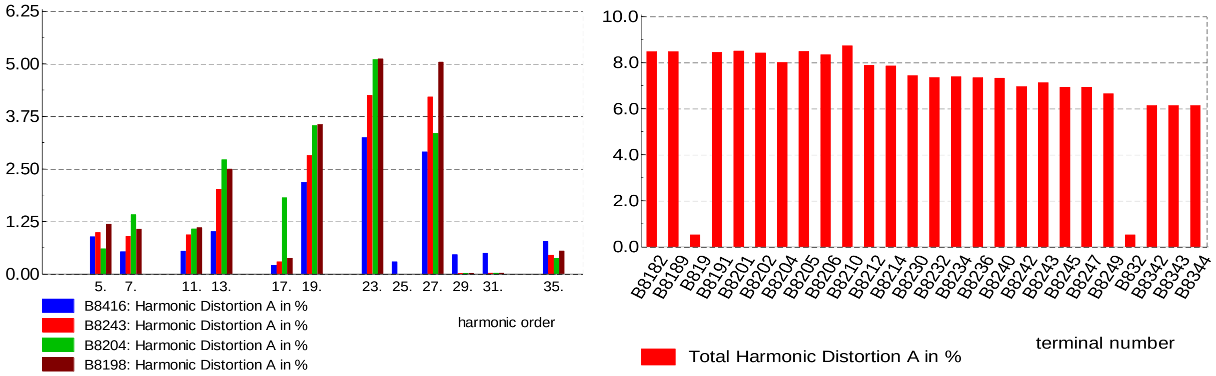

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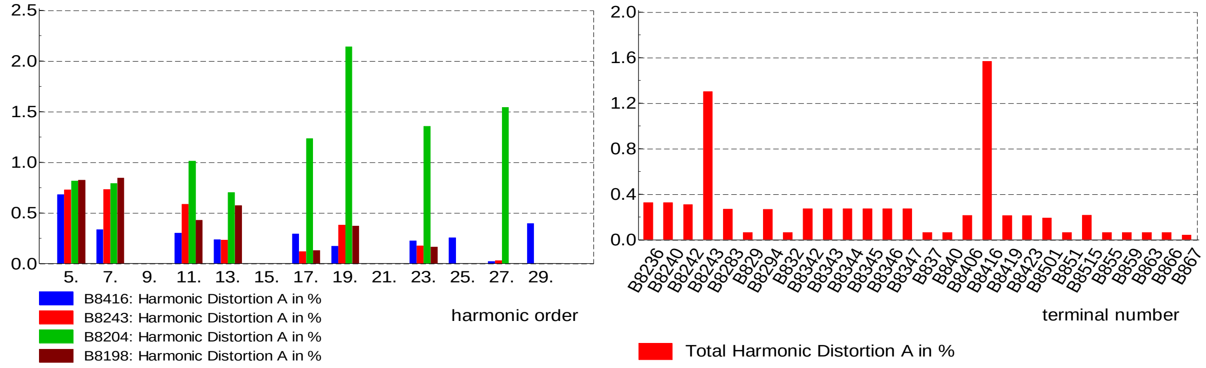

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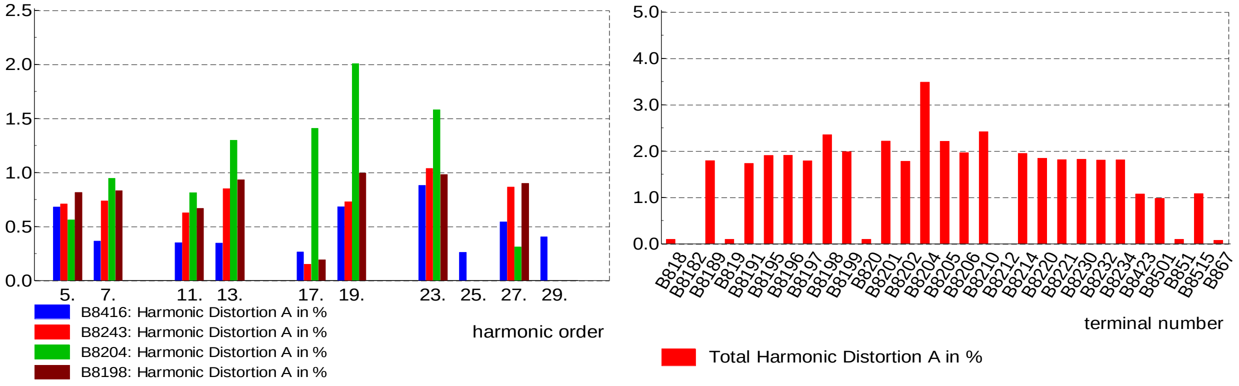

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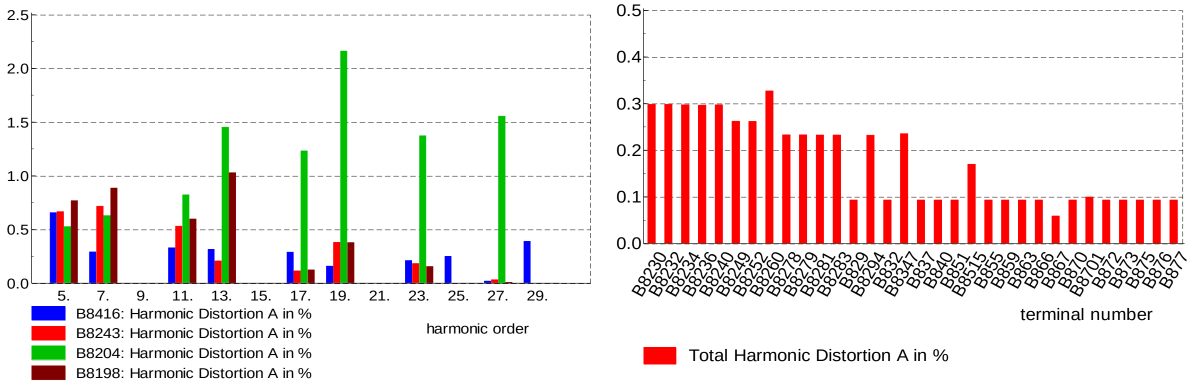

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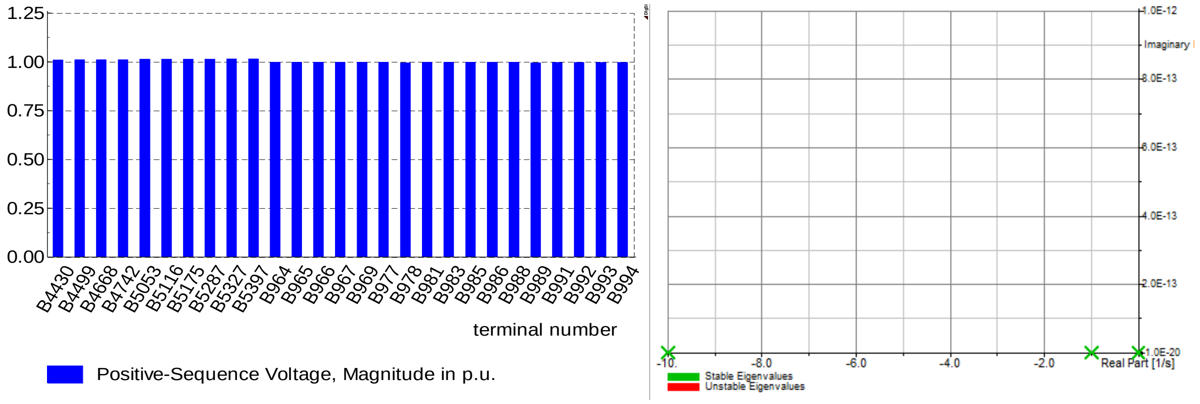

(a) (b)

Figure 20

Tables:

Table 1

Event Name	Value	Event Explanation
NLLoad	1	Presence of non-linear load
	0	Lack of non-linear load
Stat	1	Presence of STATCOM
	0	Lack of STATCOM
Filter	1	Presence of Filter
	0	Lack of Filter

Table 2

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

Name of variables	Unit	Explanation
Speed	p.u	Speed
Phi	Rad	Rotor angle
Psie	p.u	Exitation 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

Table 4

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

Table 5

Harmonic Order	**PC Workstation** [24]		**ASD**			**Fluorescent** [24]	
	Mag. (%)	**Phase (deg.)**	**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
35	0.4	-44	0	0	0	0.1	-42
37	0.2	78	0	0	0	0	0
41	0.4	-102	0	0	0	0	0
43	0.4	-39	0	0	0	0	0
47	0.2	163	0	0	0	0.1	-137
49	0.2	-127	0	0	0	0	0

Table 6

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

Table 7

STATCOM (location)			**Passive Filter (location)**		
Bus number	18	33	Bus number	14	24
Size in MVAr	1	1	Output reactive power MVAr	1	0.7
			order	5	5

Table 8

States of system	Voltage of buses, p.u.	Stability of steady state andtransient	THD$_v$%
Normalconditions	$V_{bus} > 0.95$	Stable	Permitted range $THD_V < 5$
With presence non-linear load without STATCOM and Filter	some of 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	$THD_V < 5$

Table 9

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[25]	Light	1.4300	0.9914
	Nominal	2.659	0.9821
	Peak	3.0681	0.9658
MG-TLBO[24]	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

Table 10

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

Table 11

STATCOM (location)			Passive Filter (location)		
Terminal number	B878	B1012	Terminal number	B3752	B926
Size in MVAr	0.5	0.5	Output reactive power MVAr	1	1
			order	5	5

Biographies

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