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ORIGINAL PAPER

RFLSA control scheme for power quality disturbances mitigation in DSTATCOM with n-level inverter connected power systems

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Abstract

In this paper, a hybrid control scheme is proposed for power quality mitigation in DSTATCOM connected n-level inverter system. The proposed hybrid control scheme is the joined execution of both the random forest search algorithm and lightning search algorithm (RFLSA). The novelty of the proposed hybrid control scheme is enhanced prediction capability with the involvement of lightning search algorithm (LSA), reliability, adaptive for all parameter variations and less execution time. Here, the gain parameters of the PI controller are predicted to provide the optimal control signal of the DSTATCOM using proposed RFLSA technique. The proposed method prediction process considers all type of variations in the system parameters like DC voltage, real and reactive power. Based on the minimum error objective function, the learning process of random forest search algorithm (RFSA) is enhanced by using the lightning search algorithm (LSA). Then, the proposed technique is implemented in the MATLAB/Simulink platform and the performance is evaluated. The behavior of the proposed technique has been successfully compared with existing techniques. Simulation results shows that the proposed technique has the capability of ensuring satisfactory dynamic response, high efficiency and diminished harmonics.

Keywords Power quality · Power system · N-level inverter · D-STATCOM · Gain parameters · LSA and RFSA

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1 Introduction

The power utilizations have been expanded because of expanded utilization of sensitive electronic components, PCs, programmable logic controllers, security and relaying equipments. Electrical power systems are relied upon to convey power supply ceaselessly at high quality to the customers [1] due to expanding customer desires with the requirement of green energy. The economy of any nation endures with enormous misfortunes when there are voltage or current variations present in the power delivery. Failure operation of client supplies [2] because of any deviation/disturbances showed in the voltage, current and frequency from the standard rating is treated as a power quality (PQ) issues. In extensive quantities of energy sources, transmission lines, transformers and loads [3] show in the interconnected power networks, expanding sources of disturbances happen continually which causes PQ issues fundamentally. System hardware breakdown, PC data loss and memory malfunction of sensitive loads, for example, PC, programmable logic controller controls, security and relaying equipment and erratic operation of electronic controls are caused because of PQ issues. To guarantee higher level of quality supply, for example, Uninterrupted power supply (UPS) and stabilizers and to keep these issues, clients will invest in on-site equipments despite the fact that these are expensive [1, 4].

Issues, for example, harmonics, flicker, voltage dip/swell, voltage regulation, load unbalancing and deviations in phase as well as frequency [5–8] are misrepresented because of sustainable energy integration and smart transmission systems, well furnished with current control supplies, increment the utilizations of nonlinear and electronically switched devices in distribution systems. With the objective of enhancing supplied power quality in most recent two decades [9, 10] a few solid state electronic/power-electronic devices have been created, contemplated and proposed to the global academic group. As needs be, the reliability and quality of power that is conveyed to clients is upgraded by the FACTS based power electronic controllers for distribution systems, specifically custom power devices. Probably the most cost effective solutions for these sorts of power quality issues [11, 12] are in many occurrences, the utilization of a Distribution Level Static Compensator (D-STATCOM).

In the distribution network [13–15], D-STATCOM can adjust the reactive power, load unbalancing, voltage varieties and current harmonics. To upgrade the power quality [18, 19] the control strategies of DSTATCOM [21, 22] like Instantaneous power theory [16], synchronous reference frame theory (SRF), modified synchronous reference frame theory (MSRF), instantaneous symmetrical control theory [17] and average unit power factor theory (AUPF) have been produced. The quality of power systems [20] might be influenced by those strategies that unavoidably exist the issues of over or under compensation. Here, a combined execution of random forest search algorithm and lightning search algorithm (RFLSA) technique for D-STATCOM with n-level inverter is utilized. Plainly described in detail is the proposed technique. Talked about in Sect. 2 is the remainder of this article, the recent research work and the background of the research work which is organized as follows. In Sects. 3 and 4 thorough explanation of the proposed technique is explained. In Sect. 5, the suggested technique achievement results and the related discussions are given and Sect. 6 concludes the paper.

2 Recent research works and problem formulation

Several research works have previously existed in literatures which are based on the power quality enhancement of D-STATCOM using various techniques and various aspects. Some of the works are reviewed here.

Lei et al. [23] have presented a novel integrated structure for a cascaded distribution static compensator (D-STATCOM) and distribution transformer for medium-voltage reactive power compensation. The three-phase winding taps were symmetrically arranged and the connection point voltage can be decreased to half of the line-to-line voltage at most. Thus, the voltage stress for the D-STATCOM was reduced and a compromise between the voltage rating and the current rating was achieved. The spare capacity of the distribution transformer was fully used. The working mechanism was explained and a modified control strategy was proposed for reactive power compensation. Nipun and Vivek [24] have discussed about the most important discussing topic in the world of power systems was maintenance of power quality. After generating voltage, the engineers in the substations were struggling for transmitting as well as distributing of power to the receiving end, since different loads at the ends of distribution were very sensitive to the fluctuations in the voltage, interruptions of voltage and harmonics. The improvement of Voltage Sag and THD using LCL Passive Filter along with the Distribution Static Compensator (D-STATCOM) which works with the principle of Voltage Source Converter (VSC). A new generation of static compensator, I-STATCOM behavior have been investigated by Amiar et al. [32]. In the middle of a long 400 kV line, I-STATCOM was installed. I-STATCOM is an intelligent system operator and which has the property of voltage regulator and reactive power compensator. To maintain service continuity in the severe operation modes, I-STATCOM have the capacity of breakers state changing. Furthermore I-STATCOM assists the network coupling operations synchro check, and access to the references of generator. Nesrullah et al. [33] have introduced a method for enhancing the reliability level of distribution systems. The reliability level was enhanced by an integrated voltage sag mitigation method; the methodology comprises of distribution network reconfiguration (DNR) and followed by the placement of DSTATCOM. In the first stage, during the test period to reduce the voltage sags an optimal DNR was applied. In the second stage to assist the already reconfigured network optimal placement of DSTATCOM was included in the distribution system. In the process of optimal DNR and the placement of DSTATCOM the gravitational search algorithm was utilized.

2.1 Background of the research work

Nowadays, the usage of sensitive electronic equipment has expanded which has prompt to PQ issues. The different PQ disturbances are listed as follows transients, interruptions, voltage sag, voltage swell, voltage dips, harmonics etc. To deal with these PQ issues different power devices are used. DSTATCOM is a power device used to mitigate the voltage sag, swell and harmonics. The DSTATCOM is fast, versatile and effective solution for solve the above issues. The DSTATCOM is intended for securing the whole plant with loads in the scope of some MVA. The DSTATCOM can reestablish the voltage inside couple of milliseconds. In addition, with the ideal voltage injection angle in view of least energy compensation, the target voltage function on which gives the appropriate compensation output voltage of DSTATCOM is resolved. The compensation performance of the DSTATCOM that much depends upon various control algorithms. The control algorithms like artificial neural network (ANN), fuzzy logic control (FLC) differential evolutionary (DE) algorithm, simulated annealing (SA) and so forth, are utilized together with the ideal balance of the voltage droop to vanquish the voltage sag/swell issue. The ANN and FLC are working in based on the training data, so it cannot give the proficient dynamic response and set aside more opportunity to execute or settle on the choice tenets. The DE and SA operation depends on arbitrary in nature thusly it causes infeasible arrangement with unnecessary computational time. A several configurations and control strategies are used for the DSTATCOM; however in the control algorithm requires an assistant support for finding out swell/sag/harmonic issue in system voltages to build up DSTATCOM performance. Consequently, an upgraded approach is expected to improve the DSTATCOM performance to alleviate the PQ issues in distribution system. In literature most of the works are presented to take care of this issue and the exhibited works are not giving the proficient outcomes. These issues and disadvantages have inspired to do this research work.

While comparing the proposed RFLSA with other control algorithms, the proposed RFLSA is better than the other control algorithms. Because the proposed RFLSA technique utilizes the n-level inverter based D-STATCOM which trials to mitigate the power quality complications of a power system. Here, RFLSA technique is utilized for selecting the optimal control signal of n-level inverter through optimal adjustments of the control variables in the power system. The proposed approach provides the optimal control of the D-STATCOM which tries to improve the power system damping and manage the line voltage by providing reactive power compensation. With this control technique, PQ issues are settled with precision and rapid execution to diminish the dip and surge issues in the sensitivity load linked distribution systems.

3 Proposed control structure of D-STATCOM

In power distribution network, DSTATCOM is associated in parallel with the point of common coupling which can regulate the system voltage by compensating the reactive power. Also, the DSTATCOM is utilized to enhance the stability of the power system by mitigating the power quality disturbances. Here, the proposed strategy depends on RFLSA which is helping the control algorithm for creating reference signals of n-level inverter of D-STATCOM. With this control technique, disturbances of power quality, such as, voltage sag, voltage swell and the blend of both the issues are found out with precision and quicker execution to decline the dip and surge appearance in sensitivity load connected distribution systems. By then the controlled signals are generated from the proposed technique which can generate the controlling pulses for enhancing the execution of D-STATCOM.

The proposed control structure of the DSTATCOM and installation with the transmission line is depicted in Fig. 1. The block diagram consists of a multilevel inverter associated to the distribution network by means of a coupling transformer. When the DSTATCOM is operated with a variable magnitude and phase angle, it can act as a synchronous voltage source. Accordingly, it is capable of controlling and rectifying its bus voltage and power factor respectively.

On considering the control strategy, the switch alternating can compensate the current depending upon the voltage of common coupling bus. From an energy storage capacitor, the voltage source converter engenders the output voltage of the DSTATCOM. Through the tie reactance, each output voltage is in phase and coupled to the corresponding AC voltage. When the magnitude of the generated output voltage gets distinct, the reactive power variation is controlled between the DSTATCOM and AC system. Hence, the converter compensates the reactive power if the amplitude of the output voltage is established or depressed. Due to this reason, the DSTATCOM act as a shunt compensator which can introduce an opposite remuneration current.

Assume, at the middle of the transmission line the DSTATCOM is connected which connects the generator to the network. Excluding the generators and the DSTATCOM, the network equation is represented as,

$$I_{bus} = Y_{bus} \times V_{bus} \tag{1}$$

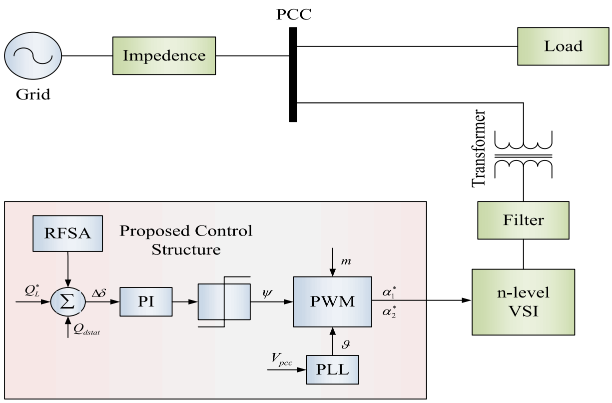

Fig. 1 Proposed control Scheme of DSTATCOM

where, the infused current is delineated as I_{bus}, the power system node voltage is represented as V_{bus} and the admittance matrix is represented as Y_{bus}. The capacitor voltage equation of the DSTATCOM is represented as,

$$\frac{dV_{dc}}{dt} = \frac{m}{C_{dc}}\left(I_{l0}^{d} Cos\phi + I_{lo}^{q} Sin\phi\right) \tag{2}$$

where, V_{dc} represents the inverter dc voltage, C_{dc} is the storage capacitor, m is the modulation index of the pulse width. I_{l0}^{d} and I_{l0}^{q} symbolizes the reference current value for d and q axis and ϕ symbolizes the phase angle of the shunt inverter voltage.

3.1 Modeling

The single phase equivalent circuit model of the shunt connected VSC and its phasor diagram is displayed in Fig. 2. The internal resistance of the coupling transformer

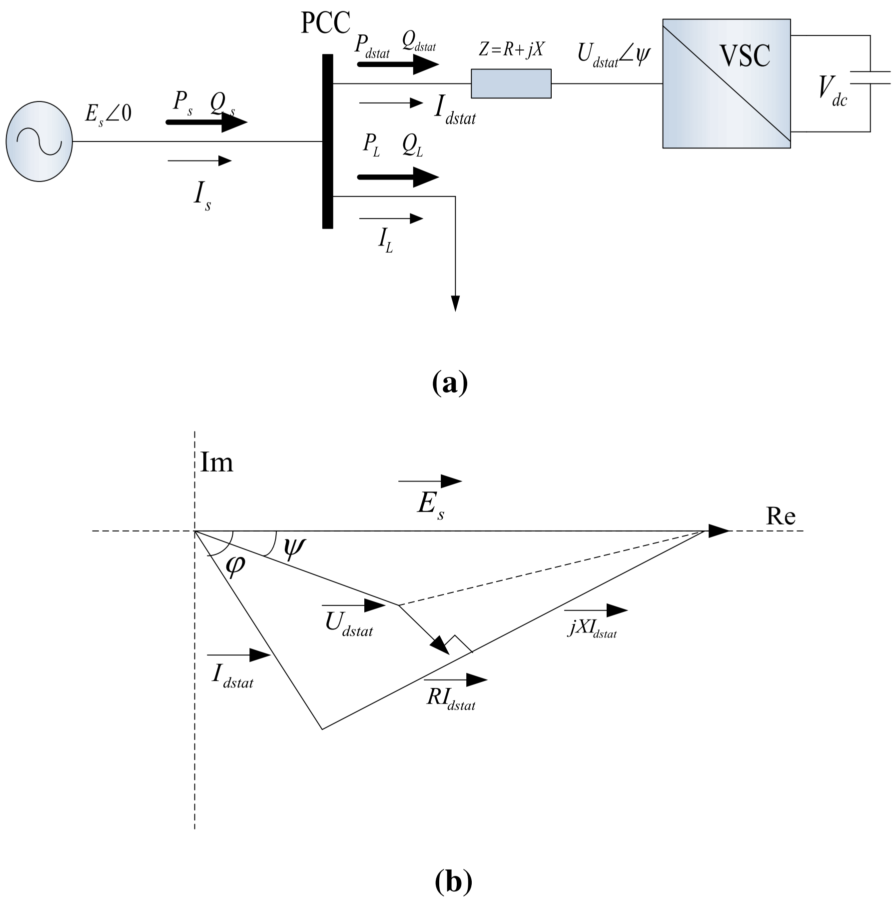

Fig. 2 **a** Single line diagram of the shunt connected VSC and **b** phasor diagram

and the internal resistance of the input filter reactors form the total series resistance R. Also, the leakage reactance of the coupling transformer and reactance of input filter reactors forms the total series reactance X. When R≪X, the converter side power flow at can be formulated as [25],

$$P_{dstat} \cong \frac{E_s V_{dstat}}{X} Sin(\psi) \tag{3}$$

$$Q_{dstat} \cong \frac{E_s V_{dstat}}{X} \left[E_s - V_{dstat} Cos(\psi) \right] \tag{4}$$

where, E_s denotes the RMS ac grid voltage at the DSTATCOM side with the phase angle of 0°, V_{dstat} is the RMS fundamental voltage of the DSTATCOM and ψ is the phase angle between them. The RMS source, RMS load and the RMS DSTATCOM fundamental currents are interpreted as I_s, I_L, and I_{dstat} respectively. The phase angle between the fundamental current and voltage of the DSTATCOM is represented as ψ. The reactive power of load and the DSTATCOM is delineated as Q_L and Q_{dstat}. The following relations are attained by acquainting the modulation index m for the assumed multilevel DSTATCOM.

$$V_{dstat} = m \frac{8 V_{dc}}{\pi} \tag{5}$$

$$P_{dstat} = \frac{8 m E_s V_{dc}}{\pi X} Sin(\psi) \tag{6}$$

$$Q_{dstat} = \frac{E_s}{X} \left[E_s - \frac{8 m V_{dc}}{\pi} Cos(\psi) \right] \tag{7}$$

In generic, by varying m, phase angle ψ, dc voltage V_{dc} or all the three, the reactive power of the DSTATCOM can be assorted contingent upon the modulation technique. In phase shift modulation (PSM), the reactive power is assorted by varying the dc voltage and the phase angle by custody the modulation index value as constant. On the other hand, in the pulse width modulation (PWM) the reactive power is assorted by varying the modulation index and phase angle by custody the constant dc voltage.

3.2 Control scheme of DSTATCOM

The main intention of the control scheme is to prohibit the system from collapse under sudden interruptions. Here, the proposed control scheme of DSTATCOM is utilized to enhance the quality of the power supply by performing functions as (1) reduces voltage and current harmonics, (2) balances the source current, (3) enriches the power factor, (4) compensate the voltage disturbances such as sag and swell and also (5) diminishes losses as well as the rating of VSI. In the reactive power control loop, PI controller is utilized which takes error signal δ as an input and the error signal is symbolized as,

$$Err\,(\delta)\,\% = \left(\frac{Q_L^{*} - Q_{dstat}}{Q_{dstat}}\right) \cdot 100 \tag{8}$$

$$Q_L^{*} = \sum \left(Q_{dstat}, Q_L, Q_s\right) \tag{9}$$

where, Q_L^{*} depicts the reference load reactive power, at the steady state condition, $Q_s = 0$ and $Q_L = Q_{dstat}$. By varying the output phase angle ψ within the reactive power generation capacity of the DSTATCOM, the operation is retained at the unity power factor by the control system. The voltage at PCC is evaluated to compute the phase angle ϑ for which phase locked loop (PLL) is applied. By assuming $\psi = 0$ on the outer control loop, the proposed algorithm computes the switching angles α_1 and α_2 with the modulation index m. In PSM, the effective switching angles α_1^{*} and α_2^{*} are computed by taking the input as ψ, ϑ,α_1 and α_2 which can accomplish both the harmonic mitigation and the reactive power regulation. The charging and discharging of the dc-link capacitor is caused by varying the phase angle and consequently the voltage at the dc link get varies by using PSM. During this voltage variation, the dc link voltage of each cell has to be balanced for the proposed n-level DSTATCOM. To perform this voltage balancing, the proposed control technique is applied. The optimization technique proposed to balance the voltage is briefly revealed in the succeeding section. Figure 3 shows the control loop of DSTATCOM.

4 Proposed optimization techniques

In this paper, a hybrid optimization technique is proposed to mitigate the power quality disturbance in the DSTATCOM with the n-level inverter. Here, the hybrid optimization is the combined performance of both random forest search algorithm and lightning

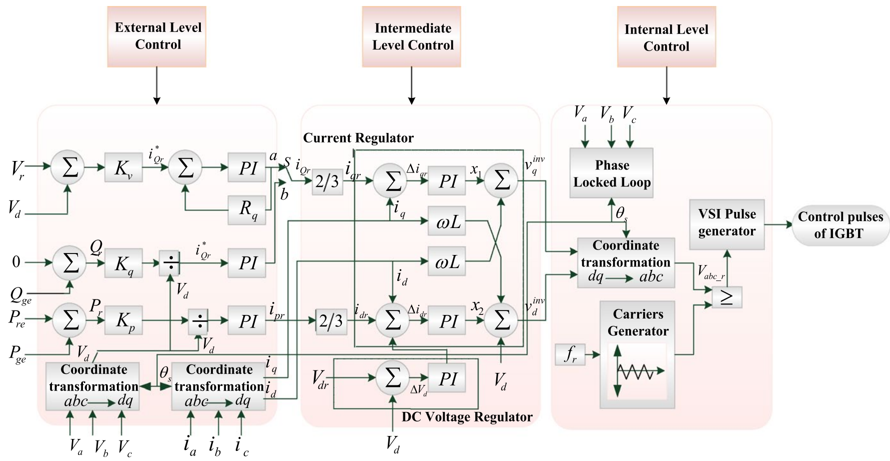

Fig. 3 Control loop of D-STATCOM

search algorithm (RFLSA) techniques. Here, the proposed technique is utilized for selecting the optimal control signal of the n-level inverter based DSTATCOM through trading edges and stage point. At the same time, it is also utilized for setting up the control signals in light of the reactive power deviation and the modulation index value. In the proposed technique, the LSA is used to enhance the learning process of RFSA in view of the minimum error objective function. The RFSA based optimal gain parameter is explained in the following segment.

4.1 RFSA based optimal gain parameter

In this section, the optimum gain parameter of PI controller is examined by the RFSA to provide the control signal of the n-level inverter. Here, the controller parameters such as voltage, current, power losses, real and reactive power values have been surveyed. Then, the optimal control parameters are attained utilizing the RFSA technique. RFSA is a well known supervised classification algorithm which manages more number of decision trees and at last, outputs the optimal individual trees in the forest [26–28]. The algorithm steps to optimize the individual trees are as follows,

Step 1 Initialize $'N'$ number of trees in the forest and the parameters such as ψ,ϑ,α_1 and α_2. The input of the algorithm is given as the reactive power deviations and the modulation index to detect the switching angles necessary to optimize the output voltage.K_p and K_i are the gain parameters of PI controller which is randomly generated

Step 2 The gain parameters are randomly selected to detect the root node by utilizing the best split. The training sets are splitted into subsets such that each subset contains data with the same value for an attribute. These processes are rendered based on the data pickup and it is expressed as,

$$I_g = -\sum_i \frac{|X_i|}{|X|} E(X_i) \tag{10}$$

where, X is the training dataset, X_i is the subset of the training dataset and the entropy of the set $E(X_i)$ defined as,

$$E(X_i) = -\sum_{j=1}^{n} P_j \log_2(P_j) \tag{11}$$

where, n is the number of sleep stages to be categorized and P_j is the proportion of sleep stage j in the set (X_i). If the earned information is positive, then the node will split otherwise it will not split and becomes a leaf node. This node is given as an input of the most common sleep stage in the training set. The determination of the best split is known as the number of leaves per tree.

Step 3 The process is replicated until the number of nodes has been reached. By replicating the above process, $'N'$ number of trees can be randomly generated. This randomly created tree forms the random forest. Once the above activity gets achieved, RFSA can able to generate the optimal gain parameters K_p and K_i of the PI controller. For the prediction of the optimal gain parameter, LSA is utilized as per the succeeding section.

4.2 Prediction using LSA

In this section, the prediction of the optimal gain parameters of the PI controller is performed. It is attained by lessening the error deviation of the reactive power. Then the optimized gain parameter is utilized to expand the finest control signal of the DSTATCOM. By utilizing the optimal control signal of DSTATCOM the power quality of the system gets enriched. The steps to accept the optimal control signal of the DSTATCOM are demonstrated in the following section [29–31].

Step 1 Initialization

Initialize the population size, maximum number of iterations, maximum channel time and the lower and upper bounds of the step leader. The error deviation is given as the input of the algorithm.

$$X = \left|(X_i)^1, \ldots (X_i)^d \cdots (X_i)^n\right| \tag{12}$$

where, $i = 1, 2, \ldots n$ is the n number of iterations.

Step 2 Random generation

Generate the random number of solution vectors pertinent to population size and the dimension as the step leader (SL).

Step 3 Evaluation

The fitness of the population is evaluated and the required fitness function is given in the following form,

$$F = Min\{\delta(t)\} \tag{13}$$

where,$\delta(t)$ represents the error deviation of the reactive power. The process gets optimized once the maximum objective function is enacted.

Step 4 Updating

Based on the fitness function, the best and worst step leaders of the input are updated. If the maximum channel time is not reached, erase the worst channel and renovate the solutions direction and the objective function value. The best and worst solution is renovated by,

$$P_l^{sl}(B) = Best\ solution \tag{14}$$

$$P_l^{sl}(W) = Worst\,solution \quad (15)$$

Step 5 Position updating

The positions of the solution are renovated by utilizing the following equation and evaluate the fitness functions of the new solutions.

$$New\left(p_{sl}^{i}\right) = p_{sl}^{i} \pm \exp\ rand\left(\mu_i\right) \quad (16)$$

Step 6 Discard worst channel

The worst channels are eliminated based on the lower energy levels and then evaluate the best channel and rank them based on the optimal solutions.

Step 7 Terminate the process

If maximum iteration is not satisfied, accession the iteration and channel time and go to step 3. Once the above procedure is completed, save the optimal results and the system is ready to provide the optimal gain parameters of the PI controller. Based on the optimal gain parameters the control signal of the DSTATCOM is elected using the proposed RFLSA technique.

5 Results and discussion

The proposed technique is implemented in MATLAB/Simulink 7.10.0 (R2012a) platform, 4 GB RAM and Intel(R) core(TM) i3. In this section, with the fault condition the proposed controller execution is dissected. In voltage regulation the execution of the D-STATCOM controller is occurred along with the harmonic lessening and current compensation. With different test cases, the model is evaluated and their results are investigated which is portrayed as below (h),

Test case 1: mitigation of power quality under voltage dip condition

Test case 2: mitigation of power quality under voltage surge condition

Test case 3: mitigation of power quality under both (dip and voltage surge) condition

The output of proposed technique displays the real and reactive power controlled in the D-STATCOM with different structures like ANFIS, Fuzzy, ANN and the proposed method. The proposed methodology presentations under different test cases are portrayed as follows.

5.1 Test case 1: Mitigation of power quality under voltage dip condition

In this section, the simulation results of the power quality mitigation under voltage dip condition Among fault condition the voltage dip arises due to extended

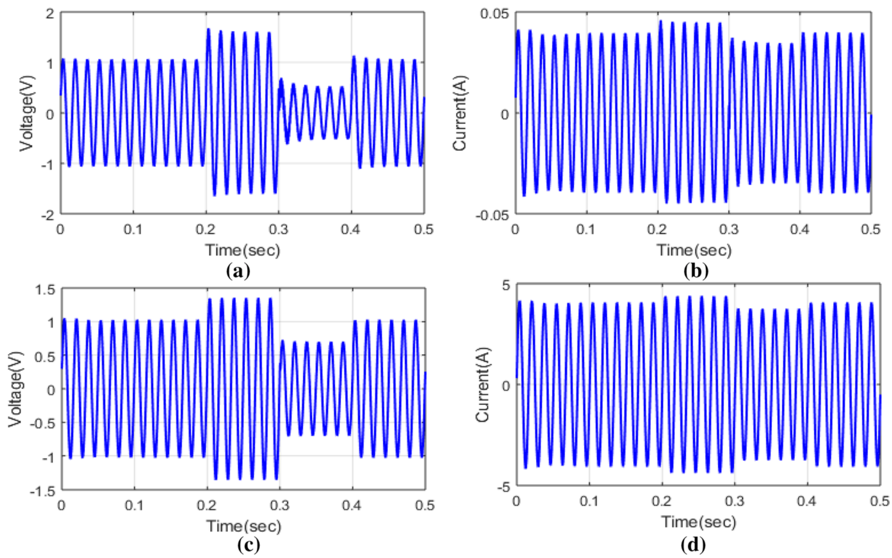

Fig. 4 Analysis of proposed method. **a** Source voltage, **b** source current, **c** load voltage, **d** load current

energy utilization and voltage fluctuation in system. The Fig. 4 illustrates the source and the load contrast of current and voltage among voltage dip condition. As observed from the figure, under voltage dip condition the amplitude of source current is deviated at 0.2–0.3 s from its nominal current by 25%, and also the source voltage amplitude reduced around 25% at 0.2–0.3 s from its nominal voltage and the voltage dip is not raised persistently. Since, if it isn't working legitimately it depends on the execution of D-STATCOM working. At that point the voltage dips are repaid by using the RFLSA based D-STATCOM controller. From its nominal value by using controller the voltage dip is raised linearly to compensate the load side voltage which is expressed in Fig. 4c, d. Thus the voltage dip is compensated by using multilevel inverter based D-STATCOM controller and their performance is presented in Fig. 5a, b.

In the above image, the D-STATCOM controller performance is dissected to the magnitude that the voltage and current midst the voltage dip condition. The proposed controller modulation index produces the optimal control signals to the multilevel inverter at voltage dip condition. Consequently, the inverter output voltage is quite compensated with optimal control signal. The proposed controller modulation index and inverter voltage in represented in Fig. 5c, d. The controller introduced proper compensating current to the PCC and in this manner the voltage in load bus is directed by the D-STATCOM will be elevated near the nominal value.

At voltage dip condition the real and reactive power is compared with the current approaches like ANFIS, Fuzzy, RNN, ORNN and the proposed method. The comparison graph of the various solution techniques with the proposed method is shown up in Fig. 6a–e. Among the transients and steady state condition,

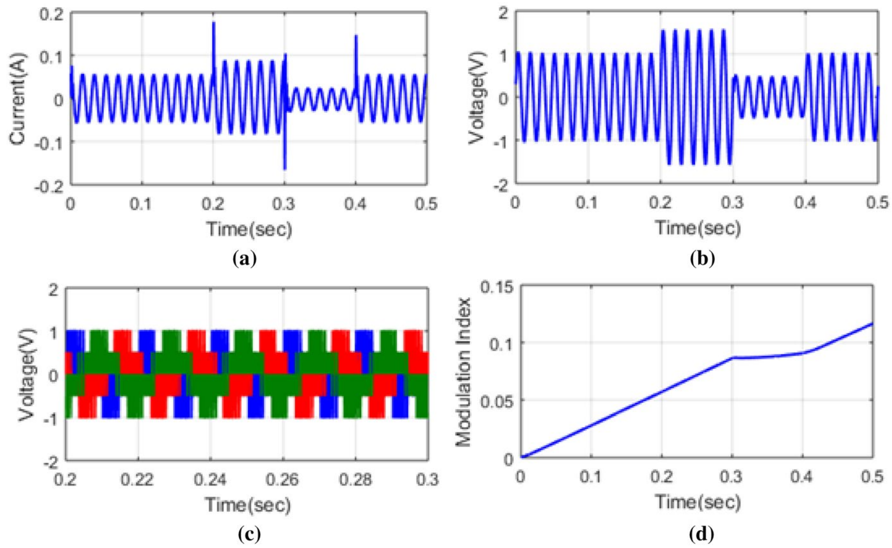

Fig. 5 Analysis of proposed method. **a** D-STATCOM current, **b** D-STATCOM voltage, **c** inverter voltage, **d** modulation index under voltage dip condition

remember the 2 s time interval of reactive power and the end objective to show that the current and voltage harmonics are satisfied as far as possible. In the graph, when t = 0 s to 0.2 s, the reactive power from the D-STATCOM is neither generated nor absorbed. At t = 0.2 s to t = 0.32 s, the D-STATCOM generates reactive power Qc = − 0.8 p.u into the grid in which Ql is practically equivalent to Qs.

The proposed dc voltage is compared with various solution techniques under voltage dip condition is shown in Fig. 7a. While comparing with various solution techniques the proposed system shows a satisfactory improvement with no overshoot and oscillations. In inductive and capacitive mode, when the D-STATCOM is not in operation the comparison of converter voltage, PCC voltage and the current among fault condition are appeared which is shown in Fig. 7b. While comparing, the converter output voltage is influenced by dc-link capacitor along with operation as continually charging and discharging the capacitor bank.

Figure 8 shows the THD voltage of proposed and the existing techniques voltage dip condition. From Fig. 8e it can be seen that the proposed method mitigates with odd harmonics from 5th to 29th. Hence the THD voltage of proposed method is less than 1% when the D-STATCOM is in operational state. When compared with the proposed to existing technique, the proposed technique efficiently mitigates the odd harmonics from 5th to 29th. Figure 9 shows the fitness of the proposed and the existing technique under voltage dip condition. In this condition, the proposed technique minimizes the PQ disturbances and improves the power system quality. Under voltage dip condition based on the fitness, the solution techniques are arranged in the order of RFLSA > ORNN > ANFIS > Fuzzy > RNN.

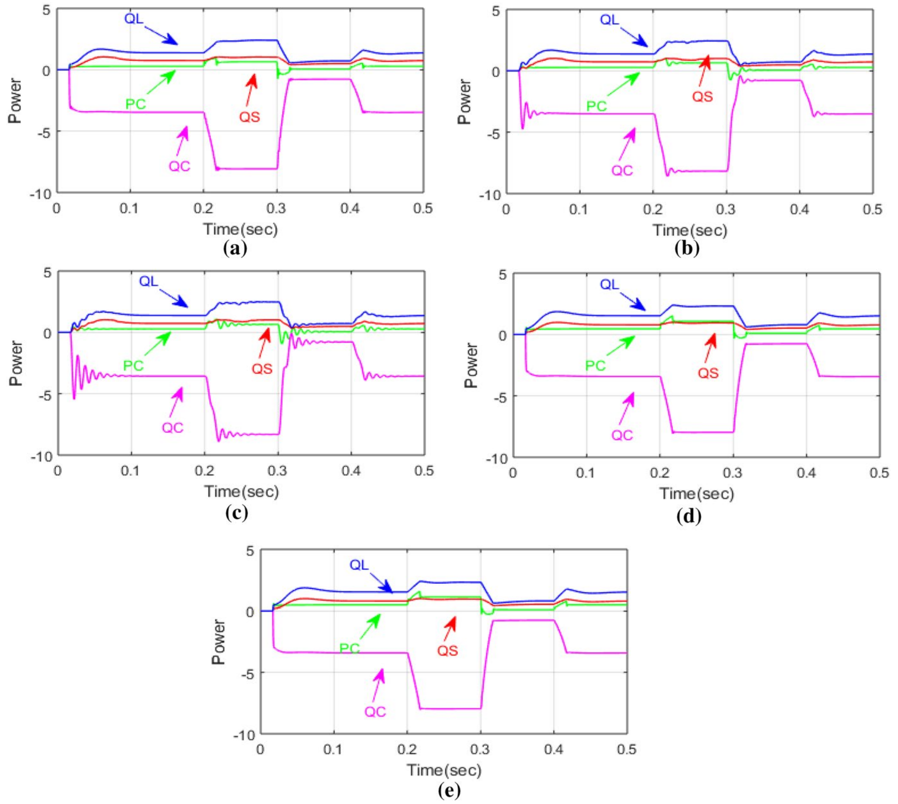

Fig. 6 Comparison: **a** ANFIS, **b** fuzzy, **c** RNN, **d** ORNN and **e** proposed method with real and reactive power

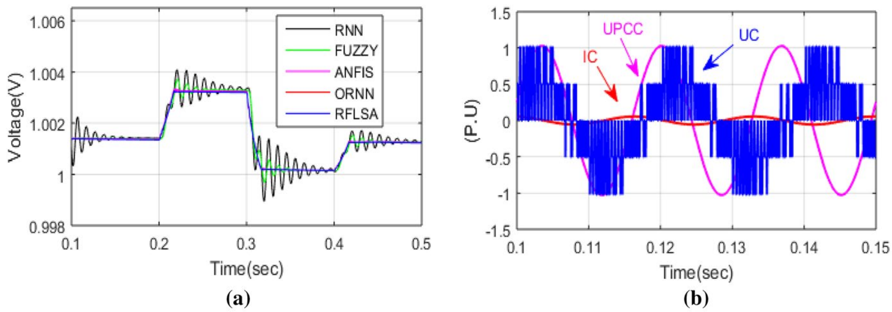

Fig. 7 Comparison: **a** dc voltage, **b** converter voltage, PCC voltage and current under voltage dip condition

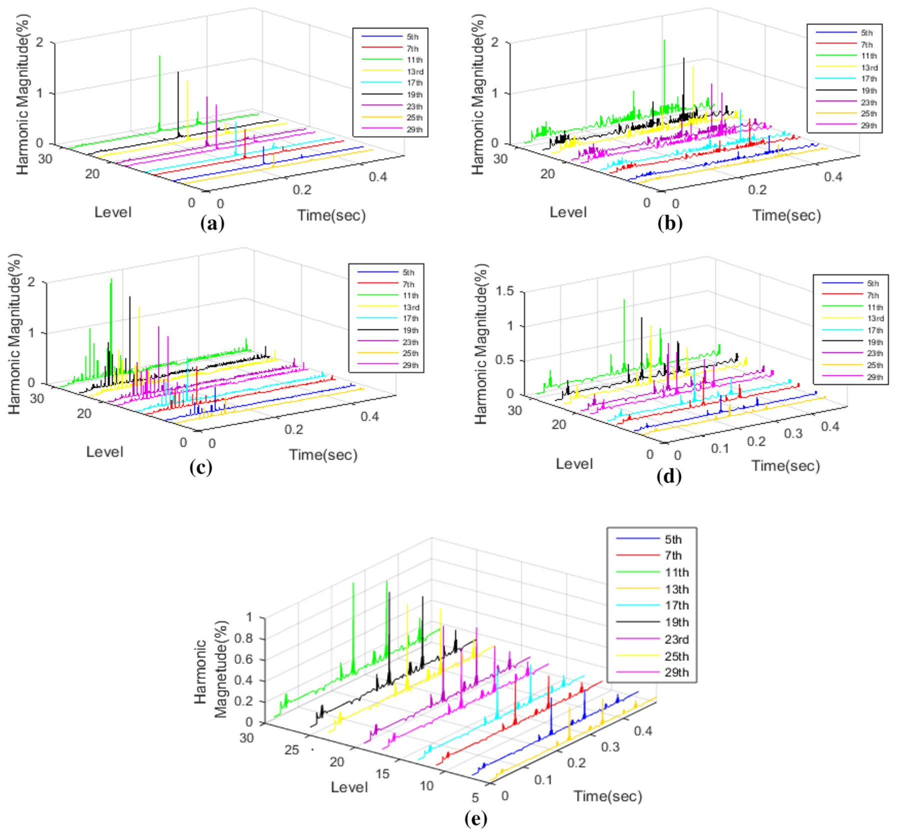

Fig. 8 Comparison of THD voltage. **a** ANFIS, **b** fuzzy, **c** RNN, **d** ORNN, **e** proposed at voltage dip condition

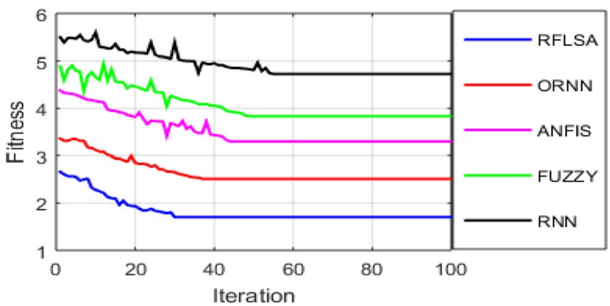

Fig. 9 Fitness of ANFIS, fuzzy, RNN, ORNN and proposed at voltage dip condition

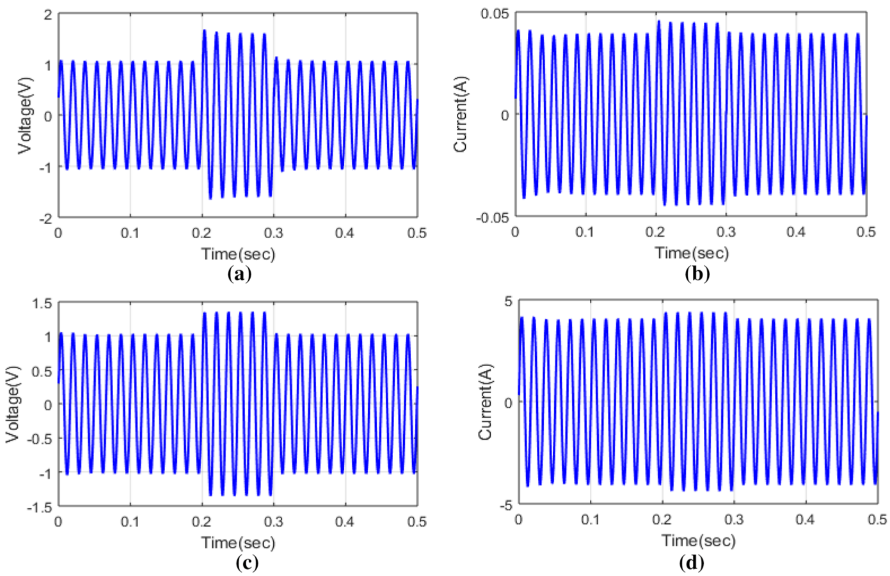

Fig. 10 Analysis of proposed method. **a** Source voltage, **b** source current, **c** load voltage, **d** load current under voltage surge condition

5.2 Test case 2: mitigation of power quality under voltage surge condition

In this section, the simulation graph for the mitigation of power quality under voltage surge condition is elucidated. At primarily the voltage surge arises due to sudden decrease of load among fault condition, which impacts the high voltage in system.

The Fig. 10 illustrates the comparison of current and voltage with source and the load under voltage surge condition. As saw from the figure, under voltage surge condition the amplitude of source current is deviated in 0.2–0.3 s from its nominal current by 25%, and also the source voltage amplitude is expanded at 0.2–0.3 s around 25% from its nominal voltage and the voltage surge is not restricted continually. Hence the surge is not remunerated if D-STATCOM is not working properly. At that point the voltage surge are repaid by using the ORNN based D-STATCOM controller. From its nominal value by using D-STATCOM controller the voltage surge is repaid, which is represented in Fig. 10a, b. Essentially, the load side voltage is compensated and from the nominal value practically the voltage surge is reduced by utilizing D-STATCOM controller, which is represented in Fig. 10c, d.

In the above Fig. 11a, b, the D-STATCOM controller performance is dissected to the magnitude that the voltage and current midst the voltage surge condition. The proposed controller modulation index produces the optimal control signals to the multilevel inverter at voltage surge condition. In this way the inverter output voltage is solely compensated with optimal control signal. The proposed controller modulation index and inverter voltage in represented in Fig. 11c, d. From PCC the D-STATCOM controller absorbs the proper compensating current and in this

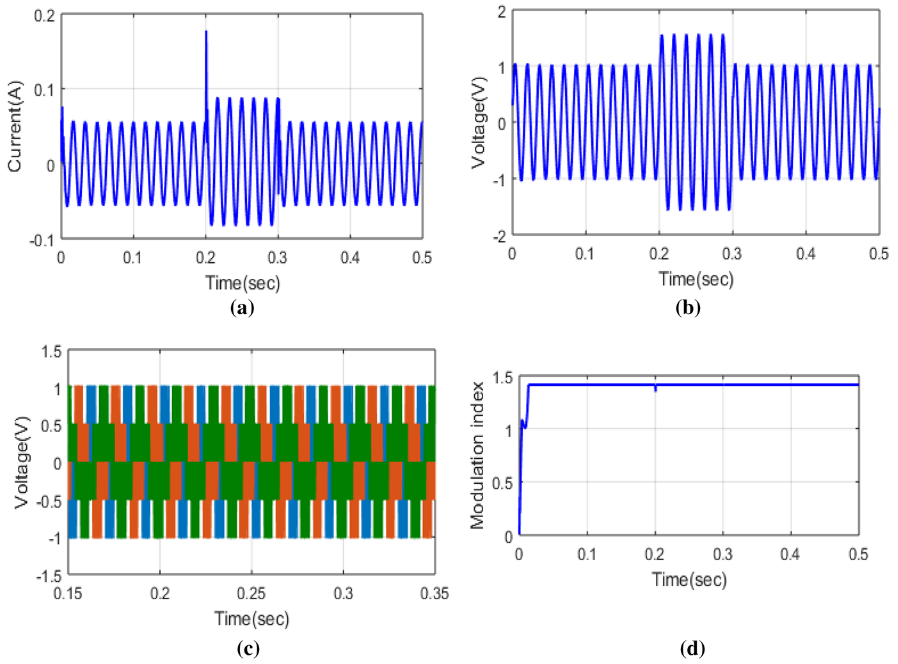

Fig. 11 Analysis of proposed method. **a** D-STATCOM current, **b** D-STATCOM voltage, **c** inverter voltage, **d** modulation index under voltage surge condition

manner the D-STATCOM handled the load bus voltage which is deserted near the nominal value.

Under voltage surge condition the real and reactive power is compared with the current approaches like ANFIS, Fuzzy, RNN, ORNN and the proposed method. The comparison graph of the various solution techniques with the proposed method is shown up in Fig. 12a–e. Among the transients and steady state condition, recollect the 2 s time interval of reactive power and the end objective to show that the current and voltage harmonics are satisfied as far as possible. As per the graph when t = 0 s to 0.2 s, from the D-STATCOM the reactive power is neither generated nor inhaled. At t = 0.2 s to t = 0.32 s, the D-STATCOM ingested reactive power Qc = − 8 p.u into the grid in which Ql is practically equivalent to Qs. In the course of inhaled Qc into the network the proposed system shows a satisfactory improvement with no overshoot and oscillations when compared with various solution techniques.

The proposed dc voltage is compared with various solution techniques at voltage surge condition is shown in Fig. 13a. In inductive and capacitive mode, when the D-STATCOM is not in operation the comparison of converter voltage, PCC voltage and the current among fault condition are demonstrated which is shown in Fig. 13b. The THD voltage of proposed and the existing techniques at voltage surge condition is depicted in Fig. 14. The proposed method mitigates with odd harmonics from 5th to 29th and it can be presented in the Fig. 14e. When the D-STATCOM is in operational state, the THD voltage of proposed method is less

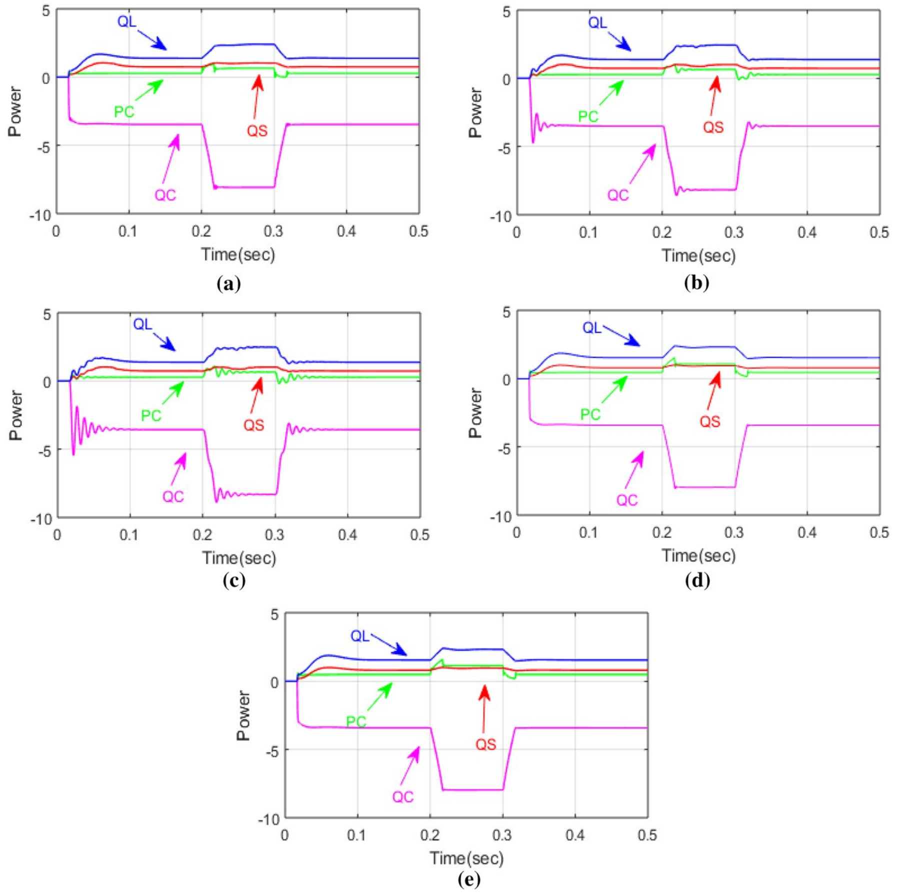

Fig. 12 Comparison: **a** ANFIS, **b** fuzzy, **c** RNN, **d** ORNN and **e** Proposed method with real and reactive power under voltage surge condition

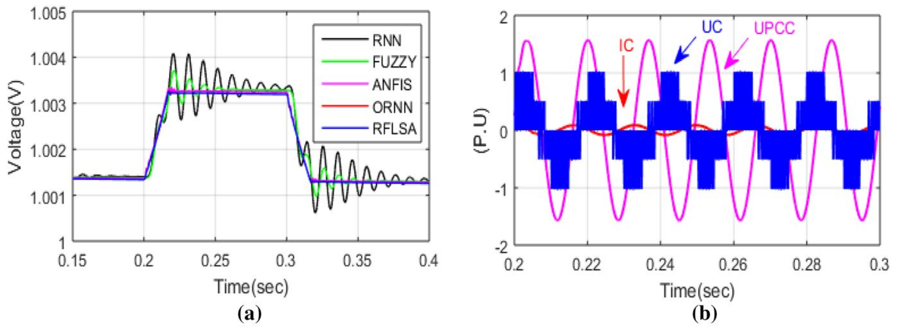

Fig. 13 Comparison: **a** dc voltage, **b** converter voltage, PCC voltage and current under voltage surge condition

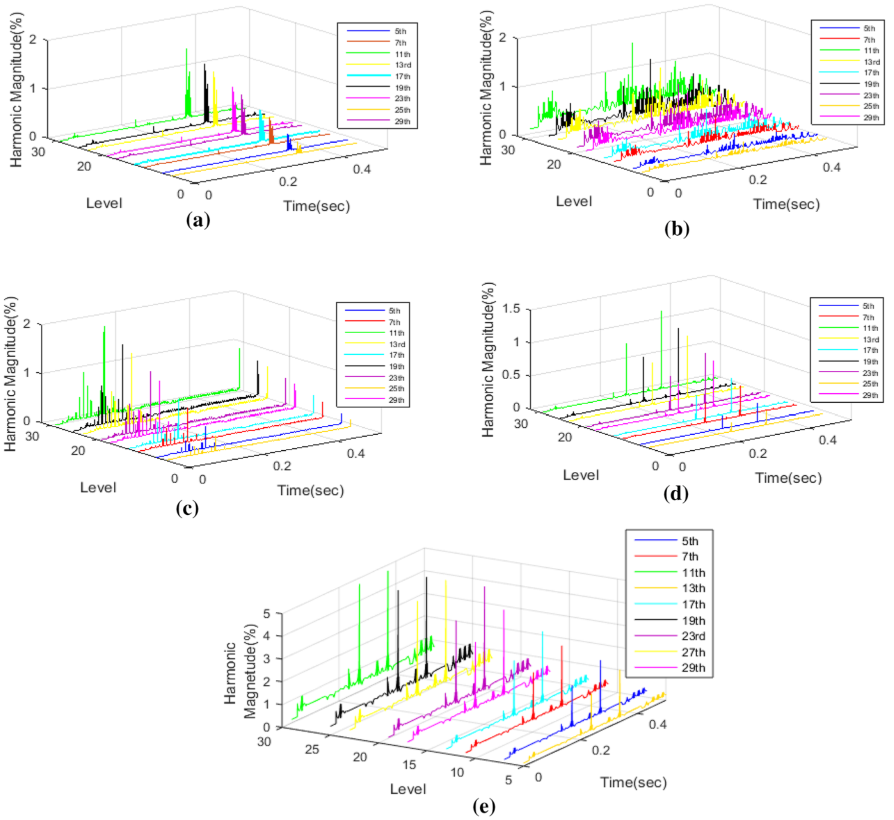

Fig. 14 Comparison of THD voltage **a** ANFIS, **b** fuzzy, **c** RNN, **d** ORNN, **e** proposed under voltage surge condition

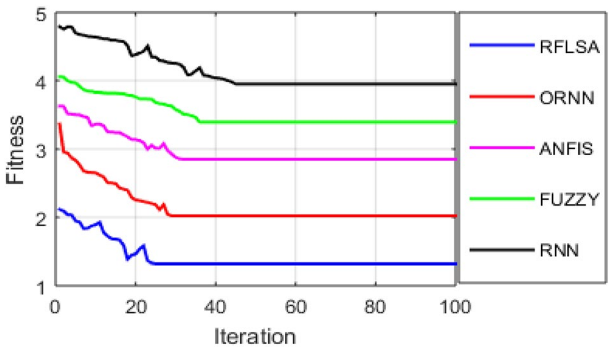

Fig. 15 Fitness of ANFIS, fuzzy, RNN, ORNN and proposed under voltage surge condition

than 1%. The proposed technique efficiently mitigates the odd harmonics from 5th to 29th when compared with the proposed to existing technique. Fitness of the proposed and the existing technique under voltage surge condition in Fig. 15.

The proposed technique minimizes the PQ disturbances and improves the power system quality under voltage surge condition. Based on the fitness, the solution techniques under voltage surge condition are arranged in the order of RFLSA > O RNN > ANFIS > Fuzzy > RNN.

5.3 Test case 3: mitigation of power quality under both (dips and voltage surge) condition

In this section, the power quality mitigation under voltage dip and surge condition is studied. Primarily the voltage fluctuation arises due to expanded energy utilization and power loss in system among fault condition. The Fig. 16 illustrates the comparison of current and voltage with source and the load under both voltage conditions. As saw from the figure, the amplitude of source current is deviated from its nominal current by 25%, and also the source voltage amplitude is expanded around 25% from its nominal voltage under voltage surge condition and the voltage variation is not reduced continuously. Hence the voltage variation is repaid if D-STATCOM controller is working properly. From its nominal value by using D-STATCOM controller the voltage variation is remunerated, which is shown in Fig. 16a, b. Essentially, the load side voltage is compensated and from the nominal value practically the voltage variation is mitigated by utilizing D-STATCOM controller, which is represented in Fig. 16c, d.

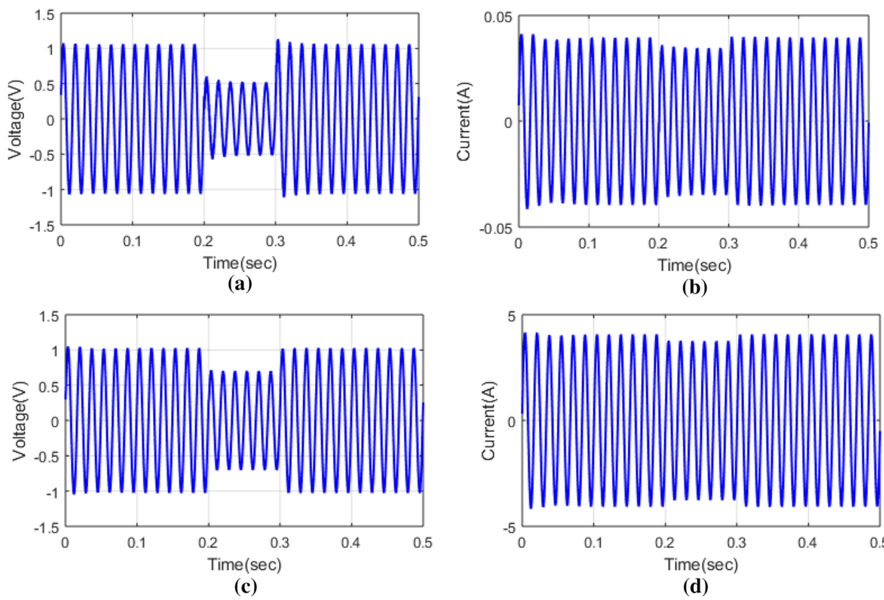

Fig. 16 Analysis of proposed method. **a** Source voltage, **b** source current, **c** load voltage, **d** load current under both (dips and voltage surge) condition

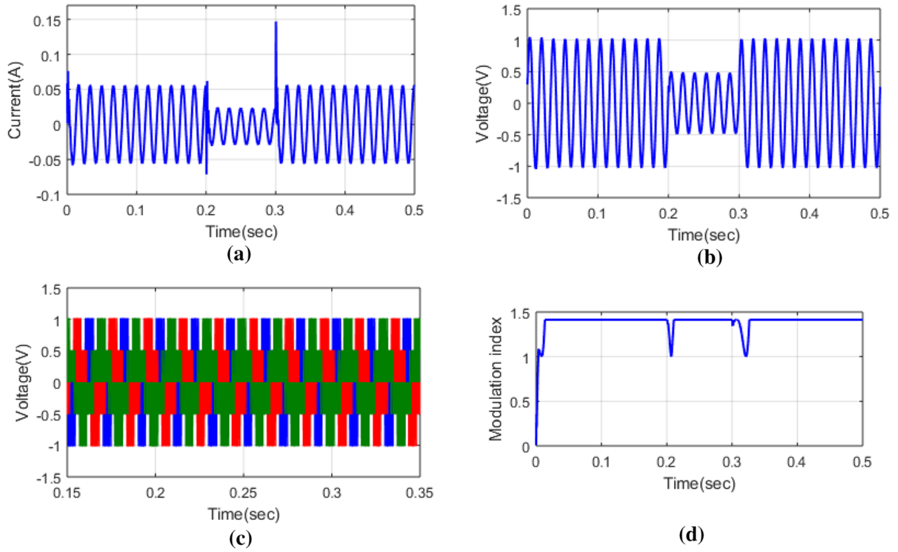

Fig. 17 Analysis of proposed method. **a** D-STATCOM current, **b** D-STATCOM voltage, **c** inverter voltage, **d** modulation index under both (dips and voltage surge) condition

In the below Fig. 17a, b, the D-STATCOM controller performance is dissected to the magnitude that the voltage and current midst the voltage variation condition. Here, at 0.3–0.4 s time interval the voltage dip occurs and voltage surge is happen in time interval 0.2–0.3 s. The proposed controller modulation index produces the optimal control signals to the multilevel inverter at both voltage conditions. In this way the inverter output voltage is completely compensated with optimal control signal. The proposed controller modulation index and inverter voltage in represented in Fig. 17c, d. From PCC the D-STATCOM controller generated or inhaled proper compensating current and at this point the D-STATCOM guided the load bus voltage which is acquired near the nominal value.

The real and reactive power is compared with the current approaches like ANFIS, Fuzzy, RNN, ORNN and the proposed method at various voltage conditions. The comparison graph of other solution techniques with the proposed method is shown up in Fig. 18a–e. Among the transients and steady state condition, remember the 2 s time interval of reactive power and the end objective to show that the current and voltage harmonics are satisfied as far as possible. As per the graph when t = 0 s to 0.2 s, from the D-STATCOM the reactive power is neither infused nor ingested. At t = 0.2 s to t = 0.32 s, the D-STATCOM ingested reactive power Qc = − 8 p.u into the grid in which Ql is practically equivalent to Qs.

The proposed dc voltage is compared with present systems at both voltage dip and surge condition is shown in Fig. 19a. In inductive and capacitive mode, when the D-STATCOM is not in operation the comparison of converter voltage, PCC voltage and the current among fault condition are demonstrated which is shown in Fig. 19b. Thus the proposed system shows a satisfactory improvement with no overshoot and oscillations when compared with present techniques like

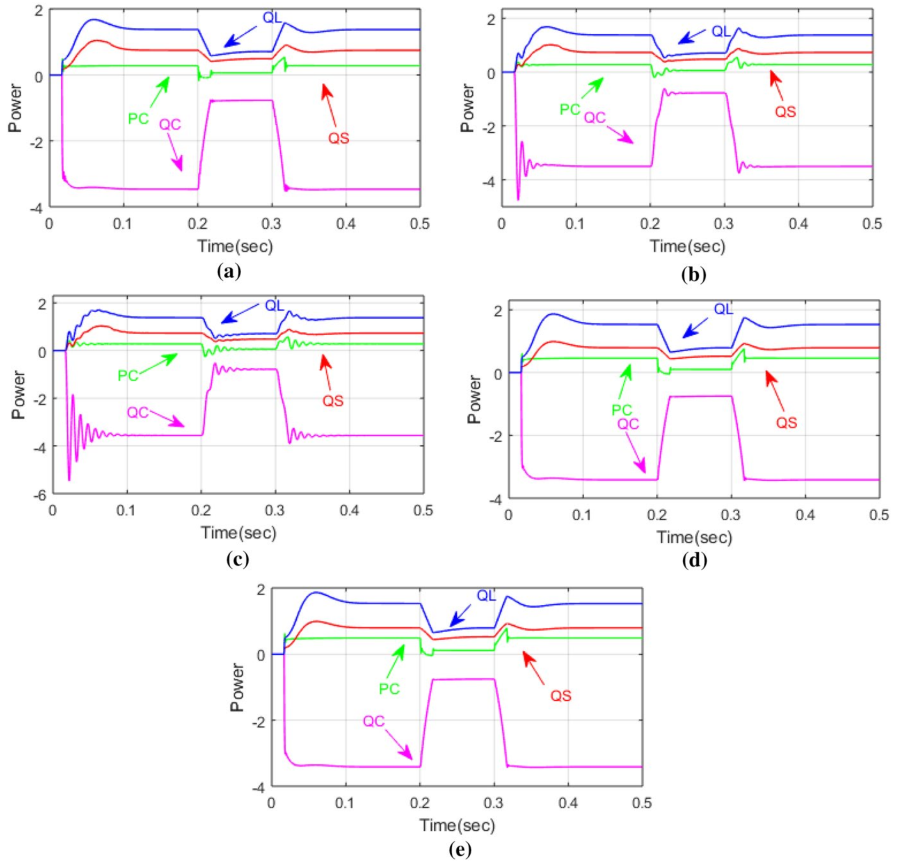

Fig. 18 Comparison: **a** ANFIS, **b** fuzzy, **c** RNN, **d** ORNN and **e** proposed method with real and reactive power under both (dips and voltage surge) condition

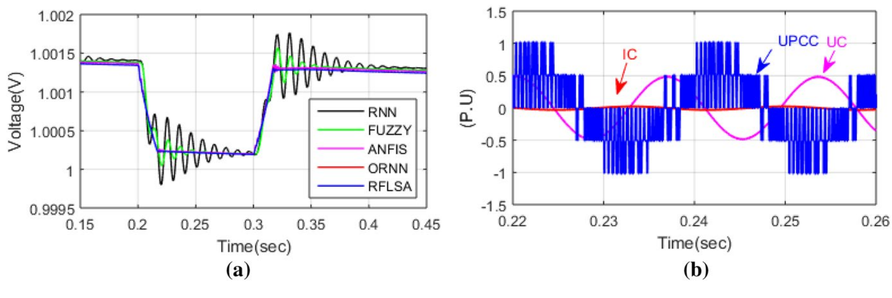

Fig. 19 Comparison: **a** dc voltage, **b** converter voltage, PCC voltage and current under both (dips and voltage surge) condition

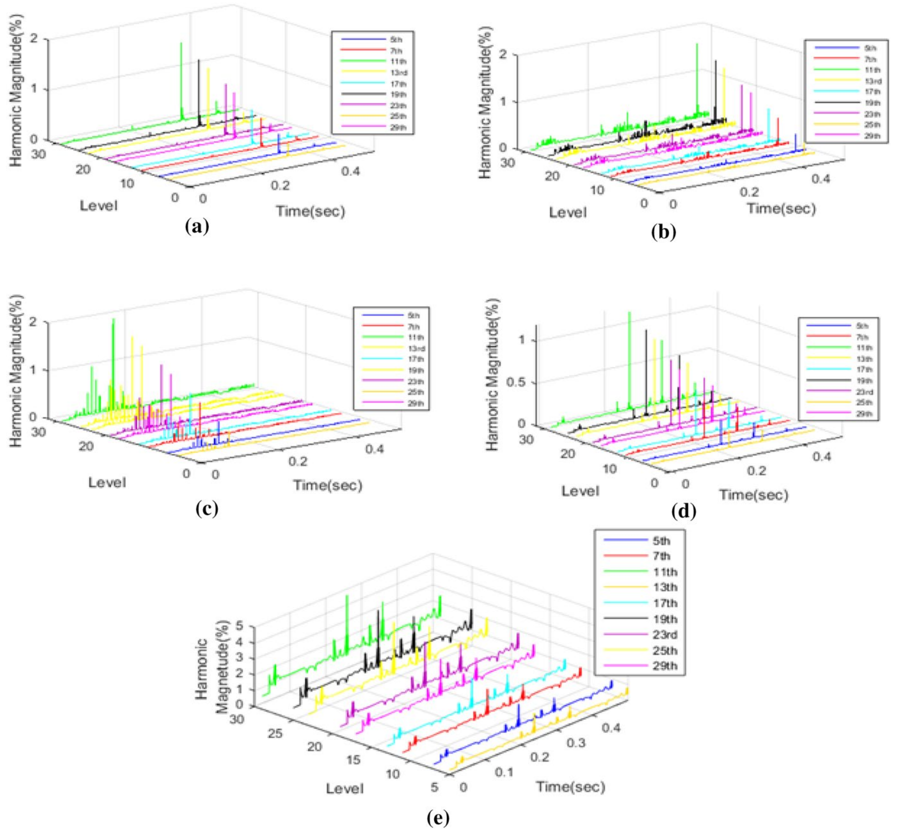

Fig. 20 Comparison of THD voltage. **a** ANFIS, **b** fuzzy, **c** RNN, **d** ORNN, **e** proposed under both (dips and voltage surge) condition

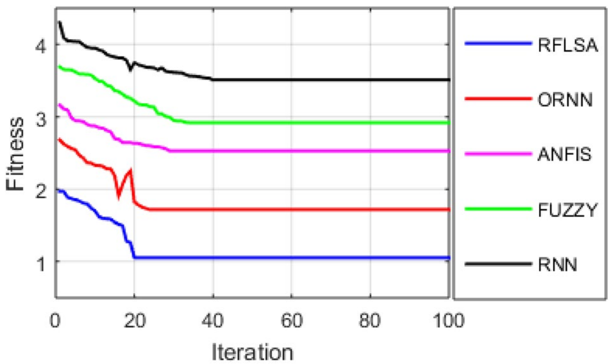

Fig. 21 Fitness of ANFIS, fuzzy, RNN, ORNN and proposed under voltage dip and surge condition

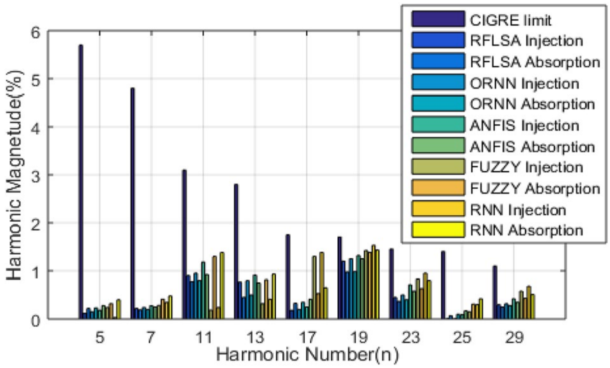

Fig. 22 nth harmonic component imposed by both the grid code

Table 1 Execution time of proposed with various solution techniques

Solution techniques	Execution time (s)
RNN	3.82
Fuzzy	4.32
ANFIS	2.90
ORNN	2.88
Proposed	2.01

ANFIS, Fuzzy, RNN and ORNN. In the above bar graph, the proposed technique mitigates with odd harmonics from 5th to 29th within the grid limits among transients and also in steady state condition.

Under both (dips and voltage surge) condition the THD voltage of proposed and the existing techniques are plotted in Fig. 20. As seen from the Fig. 20e, the proposed method mitigates with odd harmonics from 5th to 29th. Hence the proposed method THD voltage < 1% when the D-STATCOM is in operational state. By comparing the proposed with existing technique, from 5th to 29th the proposed technique mitigates efficiently the odd harmonics. Under both (dips and voltage surge) condition the fitness of the proposed and the existing technique in Fig. 21. Under both (dips and voltage surge) condition, the proposed technique minimizes the disturbances in the PQ of the system. The solution techniques are arranged based on the fitness in the order of RFLSA > ORNN > ANFIS > Fuzzy > RNN under dips and voltage surge condition.

The grid code requirement in both CIGRE WG 36-05 and the EN 50160 imposed with nth harmonic component which is appeared in Fig. 22, where the current harmonics among generated nor inhaled of responsive power are compared and the current procedures like ANFIS, Fuzzy, RNN and the proposed. Table 1 shows the execution time of the proposed as well as the other solution techniques. Here, the proposed technique execution time is 2.01 s. The execution time of RNN, Fuzzy, ANFIS, ORNN technique is 3.82, 4.32, 2.90, 2.88 s.

Thus the computational time of the proposed technique gives optimal result in less time.

6 Conclusion

A hybrid technique has been proposed in this paper for the control of DSTATCOM using n-level inverter for mitigating the power quality issues. The hybrid technique is the combined execution of random forest search algorithm and the lightning search algorithm (RFLSA). Here, the proposed technique optimizes the control signal of the n-level inverter by amending the gain parameters of the PI controller. The gain parameters are amended by the RFSA algorithm and its learning process is enhanced by LSA based on the minimum error deviation of the reactive power. Then the proposed technique is realized in MATLAB/Simulink platform and the simulation results have been contrasted with the existing controllers. On comparison, it is confirmed that the proposed technique ensures a better response in change of reference reactive power over the existing techniques.

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