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Power Quality Enhancement Using ORNN based DSTATCOM with Multilevel Inverter

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Abstract- *This paper presents a new control technique for multilevel inverter based DSTATCOM to compensate reactive power and improve the Power Quality (PQ) in distribution system. In the proposed approach, Artificial Bee Colony (ABC) algorithm is employed for enhancing the learning procedure of Optimized Recurrent Neural Network (ORNN) for mitigating the PQ issues. The ORNN technique is utilized for selecting the ideal control signal of multilevel inverter through the optimal adjustments of control variables. The proposed strategy creates an ideal control of the DSTATCOM to improve the quality of power and manage the line voltage by providing proper compensation. With this control technique, PQ issues are settled with precision and rapid execution to diminish the dip and surge issues in distribution system. This work is carried out using MATLAB/Simulink platform and the execution is assessed by comparing with various techniques like Fuzzy, ANN and ANFIS.*

Keywords: *ORNN, DSTATCOM, PQ, Distribution System, Multilevel Inverter.*

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I. Introduction

The utilization of electric power in sensitive components such as personal computers, programmable logic controllers, security and relaying equipment are increasing rapidly. Electrical power system, supplies power constantly at high quality to the customers to meet their needs [1]. The economy of power system depends on the quality of power delivery at the customer point [2]. Normally, the power quality issues are dealt extensively in terms of energy sources, transmission lines, transformers, loads and interconnected power network [3]. To ensure high quality in power supply, much investment is required in incurring of more cost [4]. The issues such as voltage dip, surge, voltage regulation, load unbalancing and deviations in phase as well as frequency [5] are generally observed due to sustainable energy integration and transmission with nonlinear and electronically switched devices in distribution system [6]. To enhance the power quality, few solid state power electronic devices have been developed and promoted globally [7].

The FACTS based power electronic controllers are implemented in distribution system to ensure the power quality [8]. The most cost effective solution for power quality issue is the utilization of Distribution Level Static Compensator (DSTATCOM) [9]. The DSTATCOM is a Voltage Source Converter (VSC) based device and is normally supported by short time energy stored in the DC link capacitor. In the distribution network [10], it can adjust the reactive power, load unbalancing and voltage variations. To enhance the power quality, the control strategies of DSTATCOM like Instantaneous power theory [11], Synchronous Reference Frame (SRF) theory, Modified Synchronous Reference Frame (MSRF) theory, Instantaneous Symmetrical Control (ISC) theory [12], and Average Unit Power Factor (AUPF) theory have been introduced. The present work focuses on enhancement of dynamic response of DSTATCOM using an Optimized Recurrent Neural Network (ORNN) control scheme for multilevel inverter.

II. Recent Research Works: A Brief Review

There are various research works which are available in the literature for power quality upgradation using DSTATCOM with different procedures and aspects. Some of the works are reviewed for better understanding of power quality issues:

To enhance the power quality, a neural network based one cycle control algorithm for 3 phase 4 wire DSTATCOM was presented by J. Jayachandran *et al.* [13]. The proposed neural network based control strategy eliminates the process of calculating the reference current with the application of voltage sensors and multipliers, thus making the system robust and simple. This algorithm is used for solving PQ problems, but it has large number of hidden layers for improving accuracy and it requires large computational effort.

P. Chittora *et al.* [14] have proposed Chebyshev Polynomials (ChP) based ANN to eliminate the hidden layer and compensate the PQ problems using DSTATCOM. However, more distortion was observed in the frequency of wavelength. The Control of DSTATCOM is usually realized by Proportional Integral (PI) controller with fixed parameters. However, the overall control performance may be unsatisfactory due to its nonlinear structure.

D. Amoozegar *et al.* [15] have presented the Fuzzy Logic Control (FLC) in DSTATCOM to improve the damping of power system.

H.Tolabi *et al.* [16] have presented a Partial Feedback Linearizing (PFL) controller for the DSTATCOM by considering the nonlinear and dynamic modeling of the DSTATCOM. The parameters of the designed controller are tuned based on the combination of fuzzy set and galaxy based search algorithm. This technique improves the response of a controller and voltage profile at the Point of Common Coupling (PCC). The parameters tuning process of this controller are time consuming, so it requires offline tuning with change in system parameters. To overcome this issue, the PFL controller parameters are tuned, according to the present error by using Mamdani based fuzzy logic concept.

S. Choudhury *et al.* [17] have designed a modified Seeker Optimization Approach (SOA) based on human searching capability to find optimum membership function parameters for fuzzy logic to increase the PI controller gains. However, the fuzzy logic controllers are used in simple configurations and their analytic knowledge is still poor.

To enhance the robustness and to simplify the controller design, Passivity Based Control (PBC) as a nonlinear controller has been investigated in power converters. Y. Chen *et al.* [18] have presented an adaptive PBC of cascaded multilevel converter based DSTATCOM integrated with distribution transformer for medium voltage reactive power compensation. A nonlinear PBC was designed to achieve reference current tracking. This adaptive PBC is used to attenuate the effect of parameters on the performance of the DSTATCOM. R. Jayaraman *et al.* [19] have focused on implementation of differential equation of the single-phase source-load system-based control algorithm for three-phase STATCOM. The presented control algorithm was employed for extraction of fundamental active and reactive current components of contaminated load currents, which are used for estimation of reference source currents. R. Agarwal *et al.* [20] have presented a Leaky Least Mean Fourth (LLMF) control technique for a single-stage three-phase grid integrated DSTATCOM system. This LLMF control algorithm is a variant of conventional Least Mean Square (LMS) algorithm from a family of adaptive filters, but it suffers from stalling due to low input signal. Hence, a leakage factor was introduced in this algorithm which improves stalling, stabilizes the system and gives a rapid convergence response. This work also controls the DC bus voltage of DSTATCOM and modifies the response of a PI controller.

G. Ramya *et al.* [21] proposed DSTATCOM with cascaded multilevel inverter to compensate the power quality issues in distribution system. The neuro fuzzy controller algorithm mitigates the power quality issues. This work is efficient for open loop system but it cannot be suitable for closed loop system. In Literature, many works are presented to resolve the power quality problems, still some improvements are required to enhance the power quality. The identified issues and disadvantages have inspired to do this research work.

III. Proposed Structure of DSTATCOM in Distribution System

The proposed design and control structure of multilevel inverter based DSTATCOM with ORNN technique in the distribution system is shown in Fig.1. The DSTATCOM is connected at Point of Common Coupling (PCC) between the source and load of the distribution network. The DSTATCOM helps to inject controlled measure of current at desired amplitude, frequency and phase angle into the grid for regulating load voltage and reactive power control. The DSTATCOM comprises of DC link voltage and 3-phase multilevel Voltage Source Inverter (VSI) which are associated with the system through filter and the coupling transformer. The DSTATCOM acts as a synchronous voltage source with a variable magnitude and phase angle. Thus, it is used for controlling its bus voltage and correcting the power factor. With heavy loading or some short circuit occurrences in the steady state operation, DSTATCOM injects suitable compensating currents at the PCC and boosts the load bus voltage to normal or given value [22].

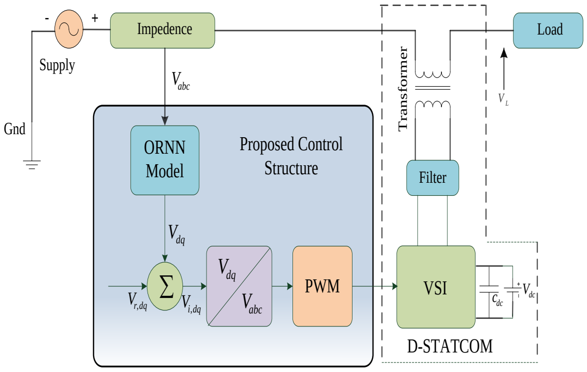

Fig. 1 Proposed control structure of DSTATCOM in Distribution system

3.1. Mathematical modeling of DSTATCOM

In a 3-phase balanced distribution network, all the losses are considered within the DSTATCOM. The equivalent circuit of DSTATCOM consisting of resistances, transformers and filters, which are represented as equivalent inductances. The inverter is considered as a perfect sine wave generator and the entire structure of DSTATCOM is shown in Fig. 2.

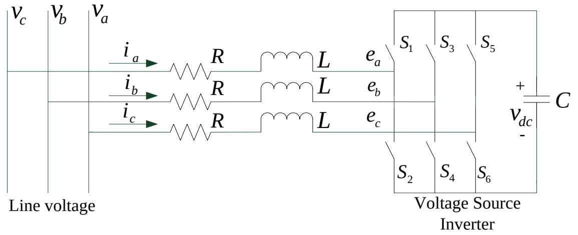

Fig. 2 Equivalent Structure of DSTATCOM

By applying electrical relations in Fig.2 the differential equations of the circuit can be rewritten as,

$$I_a = \frac{1}{L}\left[(-Ri_a) + (v_a - e_a)\right] \qquad (1)$$

$$I_b = \frac{1}{L}\left[(-Ri_b) + (v_b - e_b)\right] \qquad (2)$$

$$I_c = \frac{1}{L}\left[(-Ri_c) + (v_c - e_c)\right] \qquad (3)$$

Where,
R: Conduction losses of the inverter and transformer
L: Equivalent inductance of transformer and filter
i_a , i_b and i_c are the ac currents of DSTATCOM
v_a , v_b and v_c are the line voltages
e_a , e_b and e_c are the output voltages of the inverter.

Since the system is considered as a three-phase balanced system, it can be changed into a synchronously rotating *dq* frame [23]. At that point, the equation (1) is transformed into the following *dq* frame,

$$I_d = \frac{1}{L}\left[(-Ri_d) + \omega Li_q + (v_d - E_d)\right] \qquad (4)$$

$$I_q = \frac{1}{L}\left[-(Ri_q + \omega Li_d) + (v_q - E_q)\right] \qquad (5)$$

Where,
ω: Angular velocity of the ac voltage, current vectors
θ: Angle between the d-axis and line voltage vector

The harmonics created by the inverter are neglected by a PWM technique which is utilized in the DSTATCOM. Subsequently, ac and dc side conditions are given in equations (6) and (7) .

$$E_d = Mv_{dc} \sin \alpha \qquad (6)$$

$$E_q = Mv_{dc} \cos \alpha \qquad (7)$$

Where,
v_{dc} : Voltage across the capacitor C
M : Modulation index
α : Firing angle

The control variables M and α of the DSTATCOM can be composed as,

$$M = \frac{\sqrt{E_d^2 + E_q^2}}{v_{dc}} \qquad (8)$$

$$\alpha = \tan^{-1}\left(\frac{E_q}{E_d}\right) \qquad (9)$$

The power condition is given as,

$$P = \frac{3}{2}(v_d i_d + v_q i_q) \qquad (10)$$

$$Q = \frac{3}{2}(v_d i_q - v_q i_q) \qquad (11)$$

Where,

P : Real power of the system

Q : Reactive power of the system

The power balance condition of the inverter is given as,

$$P_i = v_{dc} C_{dc} \frac{dv_{dc}}{dt} \qquad (12)$$

The above equation is simplified as,

$$v_{dc} = \frac{1}{C}(M \cos \alpha i_d + M \sin \alpha i_q) \qquad (13)$$

Where, $C = \frac{1}{2} C_{dc}$.

The mathematical equations (4), (5) and (13) of DSTATCOM can be composed as follows,

$$I_d = \frac{1}{L}\left[(-Ri_d) + \omega Li_q + (v_d - Mv_{dc} \sin \alpha)\right] \qquad (14)$$

$$I_q = \frac{1}{L}\left[-(Ri_q + \omega Li_d) + (v_q - Mv_{dc} \cos \alpha)\right] \qquad (15)$$

$$v_{dc} = \frac{1}{C}(M \cos \alpha i_d + M \sin \alpha i_q) \qquad (16)$$

Due to the switching functions, the mathematical equations of DSTATCOM is considered as nonlinear, therefore θ is chosen as zero.

$v_q = 0$ and $Q = \frac{1}{2} v_d i_q$

It is adequate to control the reactive power Q by current i_q and furthermore it is essential to regulate the dc voltage v_{dc} in order to compensate the reactive power Q . The modeling of multilevel inverter is given in the following section.

3.2. Modeling of Multilevel Inverter

The multilevel inverter performs power conversion in terms of multilevel voltage steps to acquire enhanced power quality, lowering the switching losses, better electromagnetic compatibility and higher voltage capability [24]. The switching frequency and device ratings are constraints for high rated DSTATCOM. It is desirable to disseminate the stress among number of devices along the line [25]. The overall output voltage of multilevel inverter is given by,

$$V_{out} = V_{out}^{1} + V_{out}^{2} + \cdots V_{out}^{n} \qquad (17)$$

The inverter is said to be symmetrical multilevel inverter, when all the dc voltage sources is equal to v_{dc} . The effective number of output voltage steps (Ns) in symmetrical multilevel inverter is identified with the quantity of full bridges (n) is given by,

$$N_s = 2n + 1 \qquad (18)$$

The maximum output voltage of the n level inverter is given as,

$$V_{out}^{\max} = n * v_{dc} \qquad (19)$$

Without expanding the quantity of inverters, asymmetric multilevel inverter can be utilized to provide an extensive number of output steps. The quantity of voltage steps for n level inverter is given as,

For $j = 1, 2, \dots n$, $$N_s = \begin{cases} 2^{n+1} - 1 & if \; v_j = 2^{j-1} v_{dc} \\ 3^n & if \; v_j = 3^{j-1} v_{dc} \end{cases} \qquad (20)$$

The maximum output voltages of these n level inverters are written as,

For $j = 1, 2, \dots n$,

$$V_{out}^{\max} = \begin{cases} (2^n - 1) v_{dc} & if \; v_j = 2^{j-1} v_{dc} \\ \left(\dfrac{3^n - 1}{2} \right) v_{dc} & if \; v_j = 3^{j-1} v_{dc} \end{cases} \qquad (21)$$

In the above conditions, it can be seen that the asymmetric multilevel inverter can generate more voltage steps and maximum output voltage with a similar number of bridges.

3.3. Designing of controller

The controller of DSTATCOM contains different levels of control and each level has a specific capacity. The levels of controller are named as external control, intermediate control and internal control [26]. The external control decides the active and reactive power exchange between DSTATCOM and utility system. The intermediate control enables the expected output to dynamically track the reference value set by the external control. The internal control creates the switching pulses for VSI of the DSTATCOM. The control execution is finished with the synchronous rotating d-q reference frame. The instantaneous active and reactive power components are represented by d-axis and q-axis respectively.

a) External Control

External control performs three modes of controls such as the Voltage Control Mode (VCM), Power Factor Control Mode (PFCM) and Active Power Control Mode (APCM). When the VCM is activated, the voltage at the PCC of DSTATCOM is controlled through the modulation of reactive power component of the output current. The instantaneous voltage at the PCC is figured by utilizing a synchronous rotating orthogonal reference frame and voltage. A voltage regulation dip is incorporated to permit the terminal voltage of the DSTATCOM to differ in proportion with the compensating reactive current. When the PFCM is initiated, the reactive power reference is set to the measured values of the generated reactive power. To maintain unity power factor in the system, a standard PI controller is incorporated to reduce the steady state error in the reactive current reference component. The APCM is constantly actuated and controls the active power within the electrical system. The computation of the reference active power depends upon the injected active power. The regulated active power is given to the electrical system through DSTATCOM. A standard PI controller is additionally included to compute the steady state error from the reactive current reference.

b) Intermediate Control

The intermediate control comprises of two sections, DC voltage controller and current controller. The dynamic conditions governing the instantaneous power exchange between the DSTATCOM and electrical network are given by the equation (22) [27].

$$\begin{bmatrix} v_a^{inv} \\ v_b^{inv} \\ v_c^{inv} \end{bmatrix} - \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \left[\begin{pmatrix} R_{se} & 0 & 0 \\ 0 & R_{se} & 0 \\ 0 & 0 & R_{se} \end{pmatrix} + \frac{d}{dt} \begin{pmatrix} L_{se} & M & M \\ M & L_{se} & M \\ M & M & L_{se} \end{pmatrix} \right] \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (22)$$

Where,

$$R_{se} = \begin{pmatrix} R_{se} & 0 & 0 \\ 0 & R_{se} & 0 \\ 0 & 0 & R_{se} \end{pmatrix} \qquad L_{se} = \begin{pmatrix} L_{se} & M & M \\ M & L_{se} & M \\ M & M & L_{se} \end{pmatrix}$$

R_{se}, L_{se} are series resistance and leakage inductance of the coupling transformer of DSTATCOM and M denotes the equivalent mutual inductance of the step-up transformer.

Under the assumption that the system has no zero sequence components, all the currents and voltages can be uniquely transformed into the synchronous rotating *dq* reference frame. Thus, the new coordinate system is defined with the d-axis which is always coincident with the instantaneous voltage vector ($v_d = |v|$, $v_q = 0$), as shown in Fig. 3. Consequently, the d-axis current component contributes to the instantaneous active power and the q-axis current component represents the instantaneous reactive power. By applying Park's transformation equation (22) can be transformed into dq reference frame as follows:

$$\begin{bmatrix} v_d^{inv} - v_d \\ v_q^{inv} - v_q \\ v_0^{inv} - v_0 \end{bmatrix} = K_{se} \begin{bmatrix} v_a^{inv} - v_a \\ v_b^{inv} - v_b \\ v_c^{inv} - v_c \end{bmatrix}, \quad \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = K_{se} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (23)$$

By neglecting the zero sequence components, the state space model of the DSTATCOM in the *dq* reference frame can be summarized as follows:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\omega & -{}^{R_{se}}\!/_{L_{se}} \\ -{}^{R_{se}}\!/_{L_{se}} & \omega \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L_{se}}\begin{bmatrix} v_q^{inv} \\ v_d^{inv} - |v| \end{bmatrix} \qquad (24)$$

Where,

ω : Angular frequency of the grid voltage rotating in the *dq* reference frame.

v_d^{inv} and v_q^{inv} represents the instantaneous voltage of the DSTATCOM in d and q frame respectively.

The control strategy to get a decoupled control of the current segments i_d and i_q is getting from the above condition. To accomplish this objective, two appropriate control signals x_1 and x_2 are generated from zero derivatives of currents of equation (24). If $x_1 = i_q R_{se} / L_{se}$ and $x_2 = i_d R_{se} / L_{se}$ then equation (24) is changed with new variables as follows:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} 0 & -{}^{R_{se}}\!/_{L_{se}} \\ -{}^{R_{se}}\!/_{L_{se}} & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \qquad (25)$$

From the above equation it can be noticed that, i_d and i_q respectively respond to x_1 and x_2 with no cross coupling. In this way, the presentation of these new control variables permits to get full model, which improves the execution of the control system.

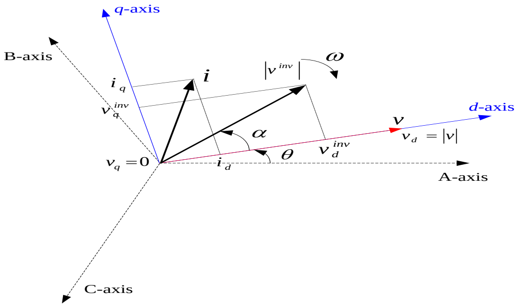

Fig. 3 Vector diagram of DSTATCOM in the synchronously rotating dq reference frame.

In DSTATCOM Power balance equation (26) is obtained by relating ac and dc side as well as input and output as,

$$P_{ac} = P_{dc} \qquad (26)$$

$$\frac{3}{2}(v_d^{inv} i_d + v_q^{inv} i_q) = \frac{-C_d v_{dc} dv_{dc}}{dt} - \frac{v_{dc}^2}{R_p} \qquad (27)$$

Where,

R_p : Resistance loss of VSI

v_{dc} : DC link voltage.

Considering,

$$v_d^{inv} = k_{inv} \cos \alpha v_{dc} \qquad (28)$$

$$v_q^{inv} = k_{inv} \sin \alpha v_{dc} \qquad (29)$$

With $k_{inv} = Ma_{vt} / 2$

Where, M is the modulation index and $a_{vt} = n1/n2$ is the voltage proportion of the coupling transformer and α is the phase shift between the converter output voltage and the grid ac voltage. The equation (27) is rewritten as,

$$\frac{dv_{dc}}{dt} = \frac{-3k_{inv}(i_d \cos\alpha + i_q \sin\alpha)}{2C_d} - \frac{v_{dc}}{C_d R_p} \qquad (30)$$

Another PI controller eliminates the steady state voltage variations at the DC bus and exchanges active power with the grid.

c) *Internal control*

The internal control is made out of a line synchronization module and a 3-phase PWM firing pulse generator for the VSI of DSTATCOM. The line synchronization module comprises of Phase Locked Loop (PLL). The PWM generator produces both frequencies in triangular wave and the firing pulses for each IGBT of the VSI by contrasting triangular wave and the desired reference 3-phase voltage wave. The detailed control algorithm of the DSTATCOM with all its essential parts is explained in Fig. 4.

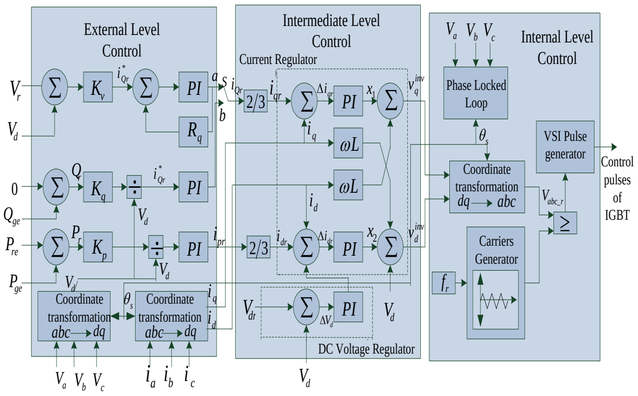

Fig. 4 Multilevel Control Scheme of DSTATCOM

3.4. ORNN Based Optimal Gain Parameter Prediction

ORNN is one of the Artificial Intelligence (AI) methods, which prepare a grouping of subjective length by recursively applying a more capacity to its interior masked state vector of the input arrangement [28].

Furthermore the ORNN technique is predominant in nonlinear frameworks due to completed interpose and extrapolate the subjective data with high precision. In the proposed method, ORNN learning process will be enhanced by utilizing the ABC algorithm in the perspective of minimum error objective function and in this way it is named as ORNN. The ORNN methodology is utilized for choosing the perfect control signal of the multilevel inverter based DSTATCOM by exchanging edges and stage point. The ORNN procedure sets up the control signals in light of the reactive power deviation and the modulation index value.

3.4.1. Training of ORNN

The Artificial Bee Colony (ABC) is a swarm insight based optimization algorithm, which works in view of the smart scavenging conduct of honey bee swarm [29]. In the ABC algorithm, the position of a food source represents a possible solution to the optimization problem and the nectar amount of a food source corresponds to the fitness of the solution represented by that food source. The stochastic ABC algorithm is able to find the global optimum with a large probability and high convergence rate [30]. Therefore, it is adopted here to train the ORNN. The algorithm steps to optimize the controller parameters are given in the following section:

Training Steps

Step 1: Initialization

Initialize the number of solutions in the population N and the number of optimization parameters D. The input of the algorithm is given as the real and reactive power values, K_p and K_i values are initialized as the random generation of PI parameters. $K_p(c)$ and $K_i(c)$ values are the current parameters and $K_p(v)$ and $K_i(v)$ values are the voltage parameters of the PI controller.

Step 2: Evaluation

The employee bee evaluates the fitness of the population and the required fitness function is given in the following equation (31),

$$F_i = Min\left(\int \Delta V_{dc}\,dt, \int \Delta I dt\right) \qquad (31)$$

Where, F_i is the value of the objective function and the process gets optimized once the minimum objective function is achieved and the corresponding K_p and K_i parameters are tuned.

Step 3: Iteration

Set the iteration count as 1, i.e., $i = 1$ where, $i = 1,2,\cdots n$

Step 4: Repeat

The process is repeated until the minimum objective function is achieved and then the selection process is carried out.

Step 5: Selection

The employed bees try to find the new solutions within the neighborhood solution. In order to produce a new solution from the old one saved in the memory, the following expression is used,

$$V_{i,j} = x_{i,j} + \phi_{i,j}\left(x_{i,j} - x_{k,j}\right) \qquad (32)$$

Where, k signifies the solution within the neighborhood of i, $\phi_{i,j}$ denotes a random number in the interval [-1, 1], $x_{k,j}$ is a randomly chosen solution which is different from $x_{i,j}$ and $V_{i,j}$ is the new solution.

Step 6: Updating

The onlooker bee attains the optimum fitness function of the new solution and determines the probability using the following expression,

$$P_i = \frac{F_i}{\sum_{i=1}^{N} F_i} \qquad (33)$$

If better solutions are not achieved, abandon the solutions and produce the random number of scout bee solution using the equation,

$$X_{ij} = X_j^{\min} + rand\,[0,1] * (X_j^{\max} - X_j^{\min}) \qquad (34)$$

Where, N is the number of solutions in population, $i = 1,2,\cdots N$ and $j = 1,2,\cdots D$. $X_j^{\min}$ and $X_j^{\max}$ are the lower and upper limits of the j^{th} optimization variable, $rand\ [0,1]$ denotes a uniformly distributed random number within [0, 1].

Step 7: Termination

Save the best solution achieved so far and minimize the error values of the real and reactive power variations. Then save the corresponding gain of current parameters $K_p(c)$ and $K_i(c)$ and the voltage parameters $K_p(v)$ and $K_i(v)$ of the PI controllers. Based on the above procedures, the gain parameters of both the controllers are optimally tuned. Check the iteration range, if the iteration has not achieved the maximum range, increase the iteration count as $i = i + 1$, or else terminate the process. The flowchart of the proposed technique is shown in Fig. 5.

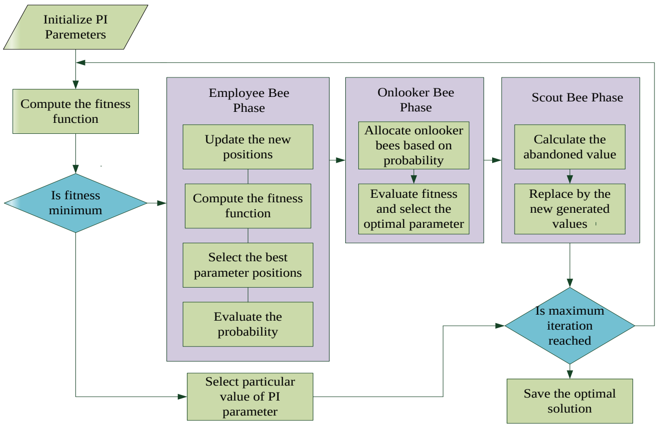

Fig. 5 Flowchart of Proposed Algorithm

3.5 Optimal design of ORNN based PI controller

From the proposed ORNN technique, the gain of current parameters $K_p(c)$ and $K_i(c)$ and the voltage parameters $K_p(v)$ and $K_i(v)$ of PI controller are optimally tuned. Based on these optimal gain parameters, the voltage signal of the inverter is optimally tuned and it provides the optimal control signal for the DSTATCOM. The optimized output of PI controller is expressed in mathematical forms as,

$$v_d^{inv} = -L\frac{di_d}{dt} - Ri_d + x_1^*(i_{dr} - i_d) + v_d + \omega L i_q \qquad (35)$$

$$v_q^{inv} = -L\frac{di_q}{dt} - Ri_q + x_2^*(i_{qr} - i_q) + v_q + \omega L i_d \qquad (36)$$

Based on the above equation, the ORNN technique compensates the input of the conventional PI controller. Therefore, the steady state error will be reduced to zero and hence improves the response speed without affecting system stability.

The proposed technique is experienced in the MATLAB/Simulink platform and its efficiency is investigated through the supplementary procedure. The voltage, current, real and reactive power is compared with different techniques from the effectiveness of the proposed ORNN technique. The detailed comparative analysis is given in section 4.

IV. Results and Discussion

In this paper, an ORNN based DSTATCOM with multilevel inverter is proposed for mitigating the power quality disturbances in distributed system. The proposed strategy is implemented in MATLAB/Simulink. The proposed strategy depends on ORNN which helps the control algorithm for creating reference signals of multilevel inverter of DSTATCOM. With this control technique, power quality disturbances, such as voltage dip, voltage surge and both are found out with precision and quick execution to mitigate the dip and surge that appear in the distribution system. The test system is given in Fig. 5a and its parameters are given in Table1.

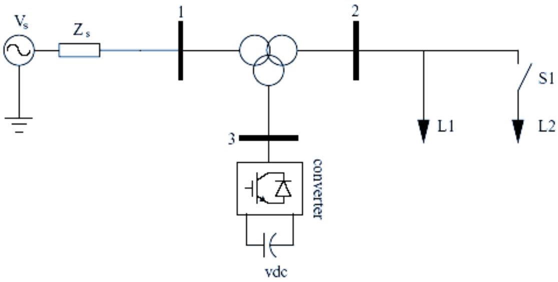

Fig. 5a. Single line diagram of the test system for DSTATCOM

Table 1 Test system parameters of DSTATCOM

Unit	**Value**
Grid voltage	400 V

Current	50 A
Nominal frequency	50 Hz
DC-link voltage	1000 V
Line inductance	2 mH
Line resistance	1 mΩ
Filter inductance	3.2 mH
Filter resistance	28 mΩ
DC-link capacitor	3000 μF
Max DC-link voltage	400 V
Load apparent power	42 kVA
Modulation Index range	5.40–8.15 p.u

a. Evaluation of performance analysis

The execution of the DSTATCOM is shown for voltage regulation and current compensation. The model is assessed and their outcomes are analyzed in various test cases as follows:

- ***Test case 1:*** Power quality mitigation under voltage dip condition
- ***Test case 2:*** Power quality mitigation under voltage surge condition
- ***Test case 3:*** Power quality mitigation under both (voltage dip and voltage surge) condition

The analyzed output of the proposed strategy exhibits the real and reactive power controlled in the DSTATCOM under various frameworks like Fuzzy, ANN, ANFIS and the proposed technique.

Test case 1: Power quality mitigation under voltage dip condition

The causes of voltage dip are due to more utilization of energy and influences the system with voltage fluctuation and fault condition. The source, load voltage and current with dip condition is shown in Fig. 6. It is observed that the amplitude of source voltage and load voltage is reduced to 25% from its normal value during t = 0.2s to t = 0.3s, which is shown in Fig (b) and (d). Also, the amplitude of source and load current deviates from its normal value by 25%, which is shown in Fig (a) and (c).If DSTATCOM is not working properly, then the voltage and current dip will not be compensated. By utilizing ORNN based DSTATCOM controller, the voltage and current dip is mitigated along the lines.

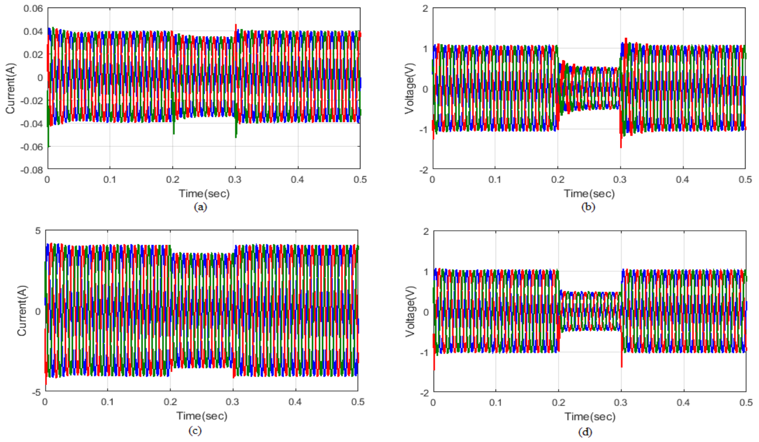

Fig. 6 Source voltage, load voltage and current with voltage dip condition (a) Source current (b) Source voltage (c) Load current and (d) Load voltage

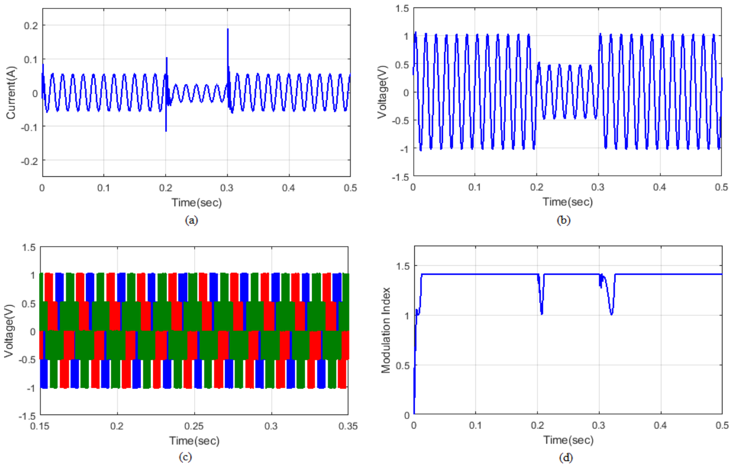

Fig. 7 Performance at voltage dip condition
(a) DSTATCOM Current (b) DSTATCOM Voltage
(c) Inverter Voltage and (d) Modulation Index

The performance of DSTATCOM and inverter voltage at voltage and current dip condition is shown in Fig.7. The DSTATCOM current and voltage is observed in Fig. 7 (a) and (b). The modulation index of the proposed controller produces optimal control signal to the multilevel inverter within dips. If DSTATCOM is not working properly, it will not compensate the voltage dip. The ORNN based DSTATCOM with multilevel inverter compensates the voltage dip near to its normal value.

The output voltage of the inverter is compensated with the optimal control signal. The inverter voltage and the modulation index of the proposed controller are shown in Fig. 7 (c) and (d). The DSTATCOM commonly injects proper compensating current at the PCC, so that voltage at the load bus is raised near to normal value.

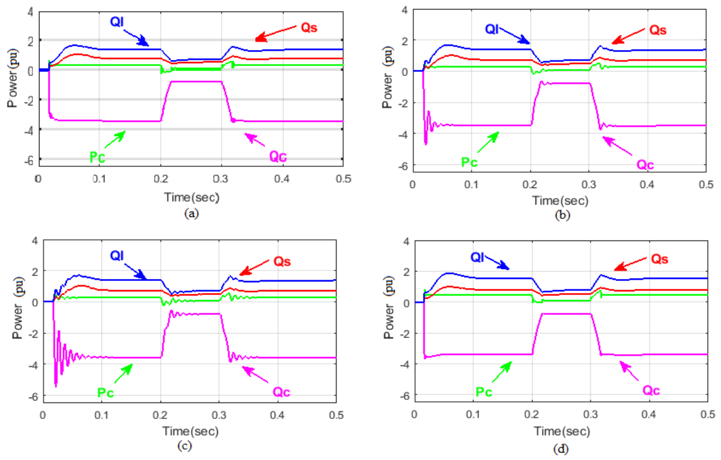

Fig. 8 Real and Reactive Power Comparison of (a) ANFIS (b) Fuzzy (c) RNN and (d) Proposed method at Voltage dip Condition.

The real and reactive power at voltage dip condition is discussed in terms of present methodologies like Fuzzy, RNN, ANFIS and the proposed technique, which are shown in Fig.8. From t = 0s to t = 0.2s, the reactive power is neither injected nor absorbed from the DSTATCOM. At t = 0.2s to t=0.3s, the dip is occurring at that time the DSTATCOM injects reactive power Qc = - 0.8 p.u into the grid in which the reactive power of load Q_l is practically equivalent to reactive power of source Q_s. When contrasted with the current procedures, the proposed technique shows a good dynamics with no overshoot and fast response time.

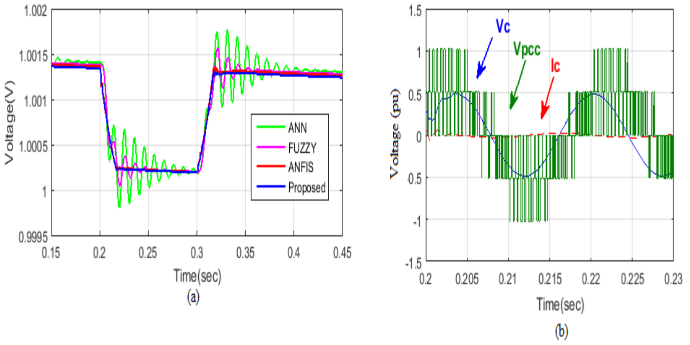

Fig. 9 Performance of (a) DC link voltage (b) Converter voltage, voltage at PCC and current at voltage dip Condition

Fig. 9 (a) demonstrates the performance of dc link voltage at voltage dip with respect to techniques like ANN, Fuzzy, ANFIS and proposed ORNN. At the point, when the DSTATCOM is not in injecting or absorbing operation, the comparison of converter voltage, PCC voltage and current at fault are shown in Fig. 9(b) for both the inductive and the capacitive mode. From the comparison, it can be seen that the dc link voltage influences the output voltage of the converter during injection and absorption as the capacitor bank continuously charges and discharges.

Test case 2: Power quality mitigation under voltage surge condition

Voltage surge is caused due to sudden decrease of the load and influences the system with high voltage in fault condition. The source voltage, load voltage and current with surge condition is shown in Fig. 10. It is observed that the amplitude of source voltage and load voltage is increased around 25% from its normal value during t = 0.2sec to t = 0.3sec, which is shown in Fig (b) and (d). Also, it is observed that the amplitude of source and load current deviates from its normal value by 25% which is shown in Fig (a) and (c).

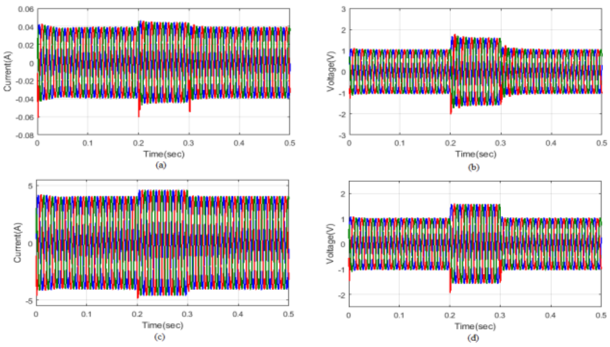

Fig. 10 Performance of (a) Source voltage (b) Source current (c) Load voltage and (d) Load current at Voltage Surge Condition

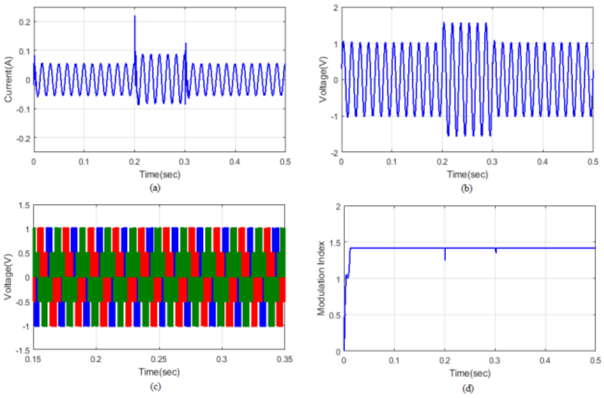

Fig. 11 Performance of (a) DSTATCOM Current (b) DSTATCOM Voltage (c) Inverter Voltage and (d) Modulation Index at voltage surge Condition

The performance of DSTATCOM and inverter voltage at voltage and current surge condition is shown in Fig.11. The DSTATCOM current and voltage is shown in Fig. 11(a) and (b). The modulation index of the proposed controller produces optimal control signal to the multilevel inverter within surge. If DSTATCOM is not working properly, it will not compensate the voltage surge. The ORNN based DSTATCOM with multilevel inverter is compensating the voltage surge nearly to its normal value.

The output voltage of the inverter is compensated with the optimal control signal. The inverter voltage and the modulation index of the proposed controller are shown in Fig.11(c) and (d). The DSTATCOM commonly injects proper compensating current to the PCC, so, that the voltage at the load bus is raised near to its normal value.

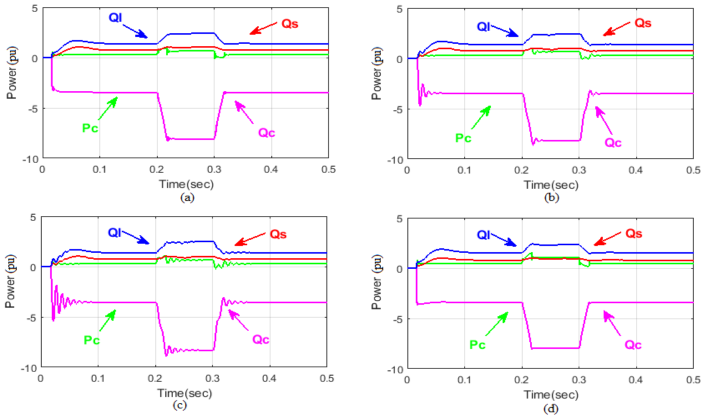

Fig. 12 Comparison of Real and Reactive Power for (a) ANFIS (b) Fuzzy (c) RNN and (d) Proposed method at Voltage surge Condition

The real and reactive power at voltage surge condition is discussed in terms of present methodologies like ANFIS, Fuzzy, RNN and the proposed strategy, which are shown in Fig.12. From t = 0s to t = 0.2s, the reactive power is neither injected nor absorbed from DSTATCOM. At t = 0.2s to t=0.3s, the DSTATCOM absorbs reactive power Q_c = - 0.8 p. u from the grid in which the reactive power of load Q_l is practically equivalent to reactive power of source Q_s. The proposed technique shows good and fast response.

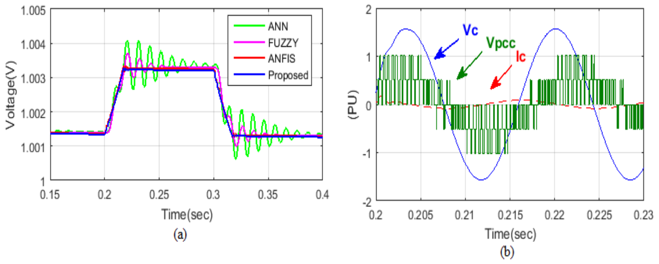

Fig. 13 Performance of (a) DC link voltage (b) Converter voltage, PCC voltage and current at Voltage Surge Condition

Fig.13 (a) demonstrates the performance of DC link voltage at voltage surge state with respect to techniques like ANN, Fuzzy, ANFIS and proposed ORNN. At the point when the DSTATCOM is not in injecting or absorbing operation, the performance of converter voltage, PCC voltage and current at surge is shown in Fig. 13 (b) for both inductive and capacitive mode. From the comparison, it can be seen that the proposed strategy demonstrates a superior response than the current systems.

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

The voltage dip and surge is examined and simulated with supply voltage, load voltage and current deviation. The voltage and current deviation is caused due to more utilization of energy and influences the system with voltage fluctuation and fault condition. The Performance of source voltage source current load voltage and load current at both voltage dip and surge condition is shown in Fig.14. It is observed that the amplitude of the source voltage is increased 25% during
t = 0.2s to t = 0.3s and diminished 25% between t = 0.3s to
t = 0.4s from its normal voltage. Correspondingly, the amplitude of source current deviates from its normal current by 25%.

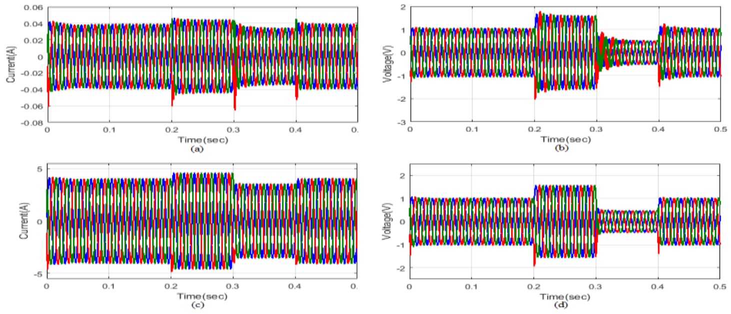

Fig. 14 Performance of (a) Source Voltage (b) Source Current (c) Load Voltage and (d) Load Current at both Voltage dip and voltage surge Conditions

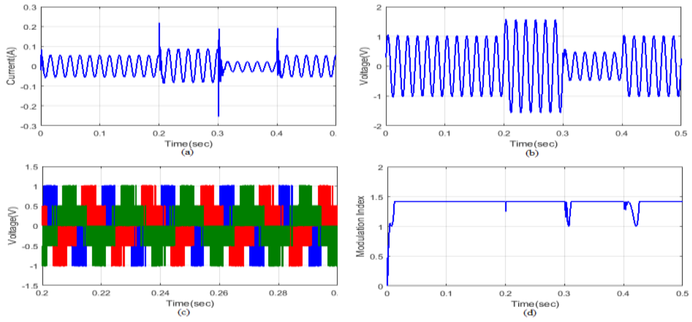

Fig. 15 Performance of (a) DSTATCOM Current (b) DSTATCOM Voltage (c) Inverter Voltage and (d) Modulation Index at both Voltage dip and voltage surge Conditions

In Fig.15, the execution of the DSTATCOM is described about voltage and current in the fault condition. The voltage surge happens in the interval = 0.2s to t = 0.3s and dip happens in the interval of t = 0.3s to t = 0.4s. The modulation index of the proposed controller produces optimal control signal for both the condition. Hence, the output voltage of the inverter is compensated with the optimal control signal. The inverter voltage and the modulation index of the proposed controller are shown in Fig. 15 (c) and (d). The DSTATCOM normally injects or absorbs proper compensating current to the PCC and voltage at the load bus.

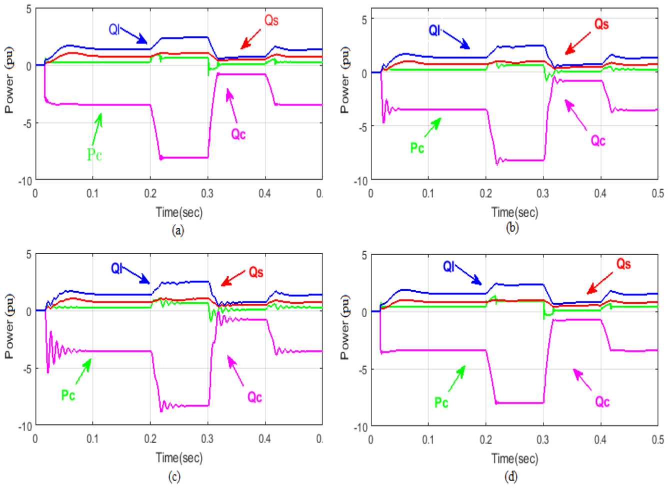

Fig. 16 Comparison of Real and Reactive Power for (a) ANFIS (b) Fuzzy (c) RNN and (d) Proposed method at both Voltage dip and Voltage surge Conditions

The real and reactive power during the voltage deviation is analyzed by the strategies like ANFIS, Fuzzy, RNN and the proposed technique, which are given in Fig. 16. The reactive power is neither injected nor absorbed from DSTATCOM between t = 0s to t = 0.2s. The DSTATCOM absorbs the reactive power Q_c = -0.8p.u between t = 0.2s to t=0.3s and injects reactive power Q_c = -0.8p.u between t=0.3s to 0.4s in the network to make Q_l is equal to Q_s .The proposed technique gives better dynamics with no overshoot and fast response.

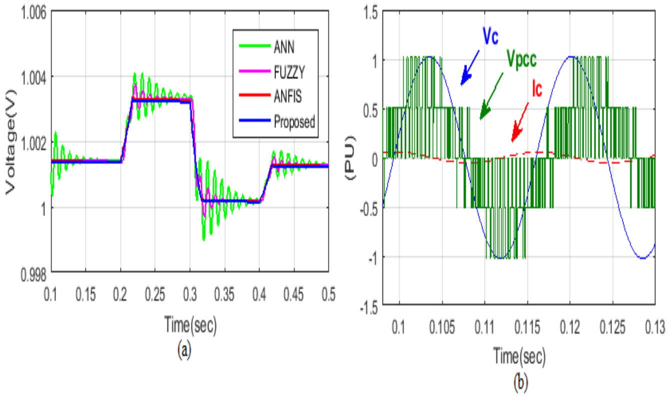

Fig. 17 Performance of (a) DC voltage (b) Converter voltage, PCC voltage and current at both voltage dip and voltage surge Conditions

Fig.17 demonstrates the performance of DC voltage in both dip and surge state, which are obtained from the techniques like ANFIS, Fuzzy, RNN and proposed method. It can be seen that the proposed strategy shows superior response. At the point when the DSTATCOM is not in injecting or absorbing operation, the performance of converter voltage, PCC voltage and current at both conditions is shown in Fig. 17 (b) for both the inductive and capacitive mode.

V. Conclusion

In this paper, power quality is enhanced by proposing an ORNN based DSTATCOM with multilevel inverter. This work improves the voltage stability of the distribution system and reduces the power loss by selecting appropriate control signal to the multilevel inverter based DSTATCOM and is implemented in MATLAB/Simulink. In the test cases, 25% of dip and surge is introduced individually and collectively to examine the reliability of the proposed technique. The voltage profile at load bus is improved to normal value by proper injection of compensating current to the PCC. At the same time, DSTATCOM injects reactive power Q_c = **-** 0.8 p.u into the grid. This work is assessed by comparing with various techniques like Fuzzy, ANN and ANFIS. The proposed ORNN system is successful in compensating the reactive power.

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