SIMULATION AND ANALYSIS OF NEW SWITCHING DYNAMICS CONTROL STRATEGY WITH FUZZY BASED NON-LINEAR SLIDING MODE OF UNIFIED POWER QUALITY CONTROLLER

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ABSTRACT:A non-linear sliding mode control (NLSMC) and new switching dynamics control strategy have been proposed for a unified power quality conditioner with fuzzy controller to improve the power quality problem in power system distribution network. The proposed non-linear sliding surface reflects the controlling action of the DC-link capacitor voltage with a variation of the system's damping ratio and permits the DC-link voltage to obtain a low overshoot and small settling time. In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. The FLC comprises of three parts: fuzzification, interference engine and defuzzification. This NLSMC technique combines with a novel synchronous-reference frame (SRF) control technique for generation of a rapid and stable reference signal for both shunt and series converters. A new switching dynamics control strategy has been designed for the voltage source converters of UPQC and this design helps in the reduction of band violation of the hysteresis band as well as improvement in the tracking behaviour of UPQC during grid perturbations. Consequently, NLSMC-SRF technique along with new switching strategy in UPQC provides an effective compensator for voltage/current harmonics, sag/swell, voltage unbalance and interruptions. . In this paper we are using the fuzzy controller compared to other controllers i.e. The fuzzy controller is the most suitable for the human decision-making mechanism, providing the operation of an electronic system with decisions of experts.

Keywords: sliding mode control (SMC), non-linear sliding mode control (NLSMC), Unified PQ conditioner (UPQC), hysteresis band (HB)

INTRODUCTION

Nowadays, power quality (PQ) issue is one of the major problems due to growing usage of non-linear power electronics loads and equipment in residences as well as in industries [1] has led to create harmonics in voltage and current. In addition, various network faults and switching of capacitor banks also create PQ issues, such as voltage sag/swell, voltage unbalance and voltage interruptions.

Unified PQ conditioner (UPQC) is a custom power device, which is one of the promising solutions for mitigating these PQ issues. A general block diagram of UPQC is depicted in Fig. 1a consisting of shunt and series converters coupled through a common DC-link capacitor. Generally shunt converter is connected in parallel with loads through the coupling inductor Lshf to compensate all current related problems [2] whilst series converter is connected in series with line through ac filter (Rsf, Lsf and Cf), switching resistor R g and series transformer for compensating all voltage related problems [3]. DC-link voltage regulation is one of the essential methodologies in UPQC and various methods such as proportional–integral (PI), PI–derivative and fuzzy controllers [4– 6] have been proposed for controlling the DC-link voltage. These controllers fail to regulate the DC-link voltage during fast transient conditions of system load and system uncertainty condition due to the failure of system components in the power disturbance network.

Hence, the DC-link voltage of the UPQC can significantly deviate from its reference value and takes finite time interval to return to its original value, resulting in performance degradation of UPQC compensation process. To ensure high performance UPQC system, the DC-link voltage should settle quickly with a low overshoot. It is a well-comprehended certainty that a low overshoot can be accomplished with high settling time and vice versa, which is not desirable in UPQC as DC-link capacitor voltage can control the operation of both shunt and series converters. The proposed non-linear sliding mode control (NLSMC) solves this particular problem, which is a combination of composite non-linear feedback (CNF) [7, 8] and sliding mode control (SMC) techniques [9].

Recently, various studies have been carried out in order to consolidate the advantages of CNF and SMC techniques. This combination of CNF and SMC is one of the preferable choices for a system with uncertainties and disturbances [10, 11]. It was shown in [12] that NLSMC has potential for match perturbations, better tracking performance, low overshoot and low settling time by varying the system's closed-loop damping ratio in its non-linear surface. Initially, the non-linear surface preserves the damping ratio at a low value and regularly varies it towards an ultimate high value to guarantee fast response, when DC-link voltage approaches a set point. Thus, this control algorithm provides an enhanced performance for regulating the DC-link voltage of UPQC. Further, the performance of UPQC depends upon how quickly and how accurately reference signal is extracted during power system dynamic condition. Hence, we consider NLSMC-SRF (synchronous-reference frame) reference generation technique by combining both NLSMC and SRF techniques. This method extracts the peak amplitude of source current and fundamental positive-sequence signal accurately during power system dynamic condition and generates the reference signal quickly. Reference signal tracking control plays an essential role in PQ improvement, generally hysteresis band (HB) current and voltage controllers [13, 14] are utilised for tracking a specified reference current and voltage for generation of pulse-width modulation (PWM) signal for controlling both converters. The HB control (HBC) method has fast response and ease in implementation in compared with other control strategies like triangular carrier PWM [15] and space-vector modulation (SVM) technique [16].

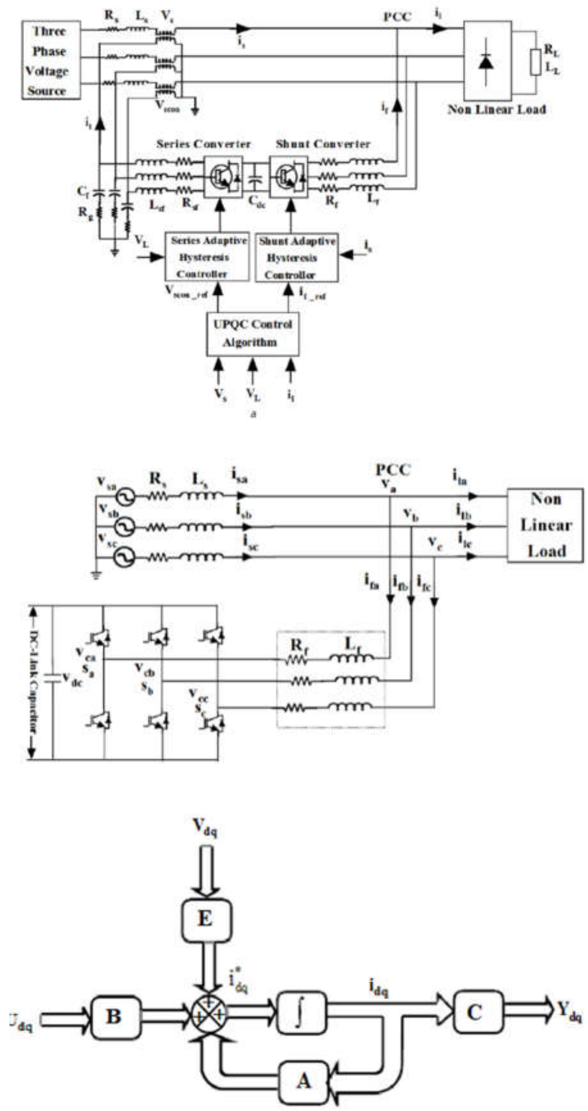
In contrast, HBC exhibits undesirable features such as band violation during grid perturbation and uneven switching frequency which gives rise to acoustic noise causing difficulty in designing of LC filter for series converter. As a result, poor compensation and serious filter currents are brought into notice. Considering above facts taken into account, a proper switching dynamics for HB needs to be developed, through which a simpler band calculation, less band violation, better tracking performance of reference signal and better injection capability of compensating current as well as compensating voltage at point of common coupling of power distribution network can be achieved.

Therefore, a new switching dynamics for HB has been proposed here and the formulation of HB depends upon the DC-link voltage regulation as well as reference signal generation. Thus, the proposed NLSMC-SRF-based new switching dynamic for HB can effectively eliminate PQ issues like current/voltage harmonics, voltage sag/swell, voltage unbalance and voltage interruptions during any operating conditions of power system perturbations.

The proposed control technique is validated through extensive simulation and real-time experimental studies accomplished by using hardware-in-the-loop (HIL) system in OPAL-RT simulator (OP5600) with OP5142 Xilinx SPARTAN-3(3xc3s5000) field programmable gate array (FPGA) processor for user interconnection. A comparative assessment has been performed between proposed control strategy, conventional NLSMC and fuzzy logic controller.

DESIGN OF NLSMC SCHEME FOR DC-LINK VOLTAGE REGULATION

Generally the shunt converter of UPQC is responsible for DC-link voltage regulation. Thus the proposed fuzzy scheme is designed for a shunt converter for DC-link voltage regulation. Schematic diagram of the shunt voltage source converter (VSC) is depicted in Fig. 1b. The conventional dynamic equations of plant model in a d–q frame are presented in (1) and (2). The plant system representation model is depicted in Fig. 1c and the step response of the proposed NLSMC scheme with initial and final damping ratios and settling time is displayed in Fig. 1d. From this step response, it can be seen that both peak overshoot and settling time are essentially low on account of the proposed fuzzy controller.



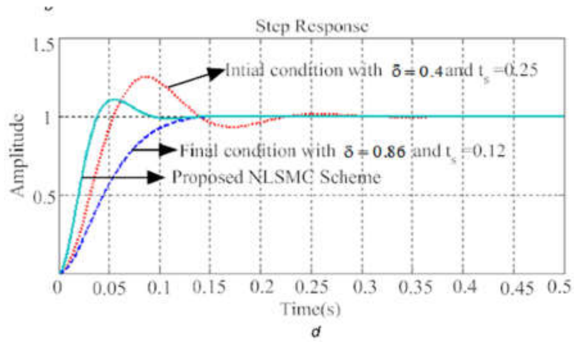


Fig. 1 System configuration and response of UPQC (a) General block diagram representation of UPQC, (b) Schematic diagram of shunt converter, (c) System representation of part of the plant model of shunt converter, (d) Step response of the NLSM method with initial and final conditions of damping ratio and settling time where

$$\frac{dX}{dt} = AX + Bu_{dq} + Ev_{dq} \qquad (1)$$

$$y_{dq} = CX \qquad (2)$$

$$X = \left[i_{d,}i_q, V_{dc}\right]^T, A = \begin{bmatrix} -\frac{R_f}{L_f} & \omega & -\frac{u_d}{L_f} \\ -\omega & -\frac{R_f}{L_f} & -\frac{u_q}{L_f} \\ \frac{3u_d}{2C_{dc}} & \frac{3u_q}{2C_{dc}} & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} -\frac{V_f}{L_f} & 0 \\ 0 & -\frac{V_{dc}}{L_f} \\ \frac{3i_{f\_d}}{2C_{dc}} & \frac{3i_{f\_q}}{2C_{dc}} \end{bmatrix}, E = \begin{bmatrix} \frac{1}{L_f} & 0 \\ 0 & \frac{1}{L_f} \\ 0 & 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where X, u dq, vdq and ydq represent the state-space vector, control input vector, input disturbance vector and control output vector, respectively. The switching function 퓮 k of the kth leg of the VSC is defined as

$$S_k = \begin{cases} 1 & if\ Sk\ is\ on\ and\ S'k\ \ is\ off \\ 0 & if\ Sk\ is\ off\ and\ S'k\ is\ on \end{cases} \qquad (3)$$

Assume v ck = 퓮 kVdc, switching state action unk is characterised as

$$u_{nk} = \left(S_k - \frac{1}{3}\sum_{j=1}^{3} S_j\right) \qquad (4)$$

To acquire a quick dynamic response, the switching state functions u d and uq are defined from (1) as

$$u_d = \frac{\lambda_d + L_f \omega i_{f\_q} + v_d}{V_{dc}} \qquad (5)$$

$$u_q = \frac{\lambda_q - L_f \omega i_{f\_d}}{V_{dc}}$$

where λ = di f/dt + Rf/Lf if. The inputs ud and uq are consisted of linear decoupling compensation term and a non-linear term. To accomplish a quick dynamic response and zero steady-state errors, the non-linear sliding surface for the system is defined as

$$s(z,t) = I_{sp} = C^T z(t) = [C1 \quad C2]\begin{bmatrix} Z1(t) \\ Z2(t) \end{bmatrix}$$
$$= \left[F - \varphi(y)A_{12p}^T \quad 1\right]\begin{bmatrix} Z1(t) \\ Z2(t) \end{bmatrix} \qquad (6)$$

where I sp is the peak value of supply current, F is the linear gain matrix, ψ(y) is the non-linear function, P is the positive-definite matrix and A 12 T can be defined from (1) by representing it to be a regular form [12]

$$A_{reg} = \begin{bmatrix} A11 & A12 \\ A21 & A22 \end{bmatrix} \qquad (7)$$

where

$$A_{11} = \begin{bmatrix} -\frac{R_f}{L_f} & \omega \\ -\omega & -\frac{R_f}{L_f} \end{bmatrix}, A_{12} = \begin{bmatrix} -\frac{u_d}{L_f} \\ -\frac{u_q}{L_f} \end{bmatrix},$$

$$A_{21} = \begin{bmatrix} \frac{3u_d}{2C_{dc}} & \frac{3u_q}{2C_{dc}} \end{bmatrix}, A_{22} = 0$$

The values of z 1(t) and z2(t) of (6) are defined as

$$z1(t) = x1y1 \quad (8)$$

$$z2(t) = x2y2 \quad (9)$$

where x 1 is obtained from the average DC bus voltage Vdc and its reference value V dc_ref

$$x_l = v_{en} = V_{dc\_ref(n)} - V_{dc(n)} \qquad (10)$$

and derivative of x 1 is defined as

$$x_2 = \dot{x_1} = \frac{1}{T}[V_e(n) - V_e(n-1)] \qquad (11)$$

where T is the sampling time. In sliding mode approach, the switching function values y1 and y2 are defined as follows:

$$y_1 = +1 \; if \; gx_1 > 0$$

$$= -1 \; if gx_1 < 0 \qquad (12)$$

$$y_2 = +1 \; if \; gx_2 > 0$$

$$= -1 \; if \; gx_2 < 0$$

where g is the switching function= c3x1 + c4x2 and c3, c4 are constants. The non-linear sliding surface defined in (6) is consisted of a linear and non-linear term. Primarily non-linear terms are zero and subsequently the linear term chooses initial damping ratio δ1 and settling time ts. From (6), c2 = 1 and c1 is defined as

$$c_1 = F - \varphi(y)A_{12}^T P \qquad (13)$$

Here F is designed for initial low damping ratio (δ1 = 0.4) and initial high settling time (ts1 = 0.25) and matrix F can be found by using pole placement technique. Locations of the poles are at −δ + δ2 − 1 ω n and −δ − δ2 − 1 ωn, where value of natural frequency of oscillation ωn can be calculated from known values of the damping ratio δ and the settling time ts. Thus ωn can be written as ω n = 4/ δts . Accordingly poles of the close-loop system are found to be placed at −16 ± 36.6606i. Using pole placement technique, the gain matrix is found as F = [0.1738 0.9723]. Considering final damping ratio as δ2 = 0.86 and settling time as t s2 = 0.12, the required gain matrix k2 can be computed as k 2 = [0.0804 0.9888] using pole placement technique.

The non-linear function ψ(y) changes from 0 to −β as output changes from its initial value to final value. It is given in [17] that introduction of this function changes the damping ratio of the system from its initial value (δ1) to the final value (δ2), where δ 2 > δ1. When ψ(y) = 0 at t = 0, the damping ratio (δ1) is contributed by F. When its output reaches to the final value, the steady-state value of ψ(y) becomes ψ(y) = − β, and the final damping ratio (δ2) is contributed by k2, therefore ψ(y) can be written as

$$\varphi(y) = -\beta e^{-\hat{\alpha} y^2} \qquad (14)$$

where α ‾ is a positive constant that should have a large value to ensure a small initial value of ψ, y is the DC-link voltage and β is the tuning parameter, which is determined by the required gain of k 2 and F. Thus, the resulting equation is defined as

$$k_2 = F + \beta A_{12}^T P \qquad (15)$$

To realise the desired damping ratio, the above equation can be equivalently expressed as

$$\beta = \frac{k_2 - F}{A_{12}^T P} \qquad (16)$$

Equation (16) decides the value of β. This parameter helps to choose the damping ratio in conjunction with matrixP, which is determined using linear matrix inequality technique based on the following equation:

$$(A_{11} - A_{12}F)^T P + P(A_{11} - A_{12}F) = -Q \qquad (17)$$

where p ∈ R2 × 2 can be chosen based on the desired final damping ratio δ 2 and Q is the negative-definite matrix.

STABILITY OF THE SLIDING SURFACE

Stability of the sliding surface is one of the important approaches in NLSMC design. Fig. 2a shows the sliding surface and its stability is determined by considering the NLSMC mode (s (z, t) = 0). From (6), the following expression can be obtained:

$$z2(t) = -Fz1(t) + \varphi(y)A_{12}^T Pz1(t) \qquad (18)$$

The system in regular form [12] can be described as

$$\dot{z_1}(t) = A_{11}z_1(t) + A_{12}z_2(t) \qquad (19)$$

From (18) and (19), the system equation during NLSMC becomes

$$\dot{z_1(t)} = (A_{11} - A_{12}F + \varphi(y)A_{12}^{T}Pz1(t) \qquad (20)$$

The stability of NLSMC technique is defined from the subsystem (20) by considering the theorem defined in [17]. Hence we apply the Lyapunov function to (20) to prove the stability of the system. Let us consider the following Lyapunov function:

$$\dot{V}(t) = \dot{z1}^{T}Pz_1(t) + z1^{T}(t)P\dot{z1}(t) \qquad (21)$$

By solving (21), it becomes

$$\dot{V}(t) = \dot{z1}^{T}(t)[-Q + 2\varphi(y)PA_{12}A_{12}^{T}P]z1(t) \qquad (22)$$

Therefore, by considering PA12 = ε, (22) becomes

$$\dot{V}(t) = \dot{z1}^{T}(t)[-Q + 2\varphi(y)\varepsilon\varepsilon^{T}]z1(t) \qquad (23)$$

Since non-linear function ψ(y) defined in (14) is negative and PA 12A12 T P = εεT ≥ 0, the matrix 2ψ(y)εεT is a negative semi definite. The matrix −Q is negative-definite and furthers the addition of a negative semi-definite and a negative-definite matrix results in a negative-definite matrix. Therefore, we can write V ˙(t) < 0, which satisfies the stability condition of NLSMC .

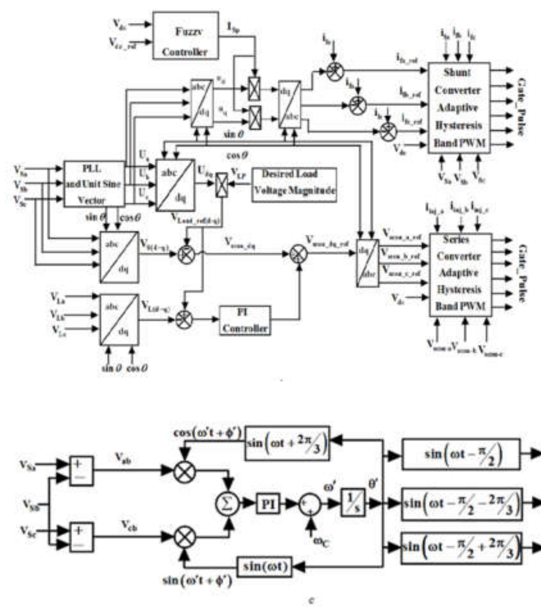


Fig. 2 Sliding surface and control strategy for reference signal generation for UPQC ((A) Proposed SRF-based control strategy for UPQC, (b) PLL circuit block diagram

PROPOSED REFERENCE SIGNAL GENERATION

The SRF-based control strategy is depicted in Fig. 2b. The SRF control method is one of the best methods for generation of reference signal during disturbance and uncertainty condition of power system network [18]. For generation of reference signal, the source voltages are applied to a phase-locked loop (PLL), where three phase unit vector signals and sine–cosine signals are generated as depicted in Fig. 2c. Three phase unit vector signals are transformed to d − q − 0 coordinate to obtain real component (ud) and reactive component (u q).

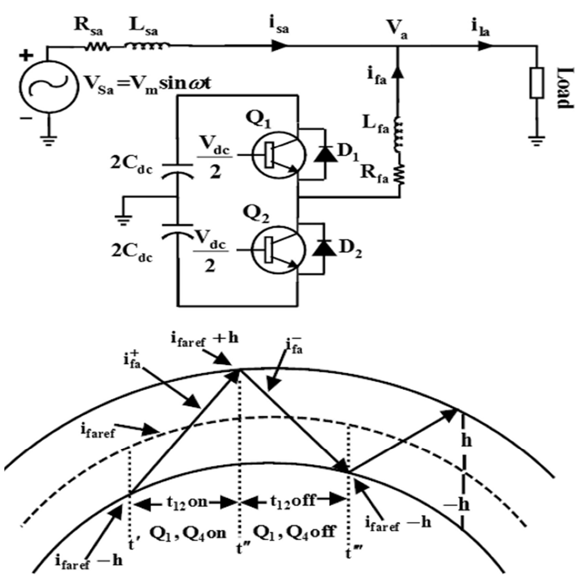
These components are multiplied with the peak amplitude of the source current (I sp), generated using fuzzy scheme and get inverse transformed to a − b − c coordinate for generating the source reference current. Compensating reference current (if_ref) is obtained by taking the difference between the load current and source reference current. For series converter, the reference voltage generation can be used for solving the voltage PQ problems. The control structure is primarily dependent on the integration of source voltage feed-forward (VS(d − q)) and load voltage feedback (VL(d − q)). The feed-forward controller delivers the essential transient response, and calculates the required compensating voltage (V scon_dq) by taking the difference between the supply voltage (Vsd − q) and load reference voltage (VLoad_ref(d − q)). However, it does not consider voltage losses due to drop across the injection transformer and LC filter.

Therefore closed-loop voltage feedback compensation VLc_dq is added to minimise losses by passing the difference between load voltage (VL(d − q)) and reference load voltage (VLoad_ref(d − q)) through the PI controller (k p = 0.20 and ki = 2.40, refer the Appendix). These losses are added to the injected compensating voltage V scon_dq to produce compensating reference voltage Vscon_dq − ref and finally inverse transformation is performed to obtain reference compensating voltages Vscon_ref.

PROPOSED SWITCHING DYNAMICS IN UPQC

Analysis of switching dynamics in shunt converter

Design of switching dynamics of shunt converter is a significant concern for controlling the switching band of hysteresis controller in transient condition. Instead of considering three-phase VSC, a single-phase VSC supported the DC-link capacitor is taken into account for simpler analysis. Fig. 3a shows schematic circuit for a single-phase shunt converter, and tracking of the reference current i faref is presented in Fig. 3b. The higher and lower boundary limits are generated by adding and deducting HBs for the compensating reference current.



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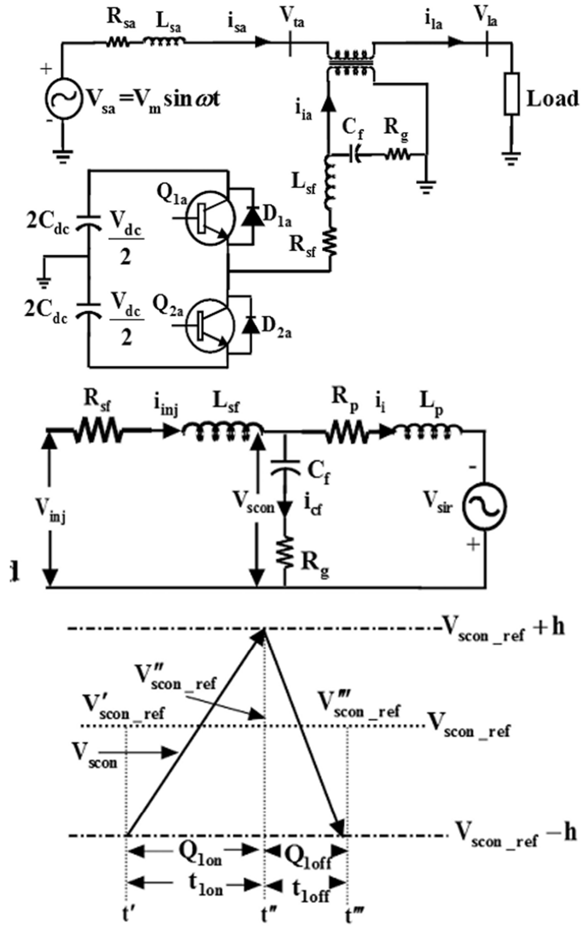


d

For tracing a positive reference current at particular time t′, switch Q1 is closed and Q2 is opened, as a result of which capacitor voltage V dc/2 is linked to converter, and also the reference current ifa + increases from (ifaref − h) to (ifaref + h). When it reaches a higher limit (ifaref + h), the reference current ifa − needs to be fetched towards the lower band. To achieve this event, switch Q1 is opened and Q2 is closed and consequently capacitor voltage −Vdc/2 is coupled to the shunt converter for rising of negative reference current slope from instant t″ to t‴.

For designing the switching band, we consider current waveform within a modulation cycle as shown in Fig. 3b. When switch Q1 conducts, the corresponding voltage equation becomes

$$\frac{V_{dc}}{2} - V_a - i_{fa}R_{fa} - L_{fa}\frac{di_{fa}}{dt} = 0 \qquad (24)$$

Then

$$\frac{di_{fa}}{dt} = \frac{1}{L_{fa}}\left(\frac{V_{dc}}{2} - V_a - i_{fa}R_{fa}\right) \qquad (25)$$

$$\frac{di_{fa}}{dt} = \frac{2HB}{t_{lon}} \qquad (26)$$

From Fig. 3b, the positive slope of the current for the duration t′ to t′′ is determined. Then on-time (t1on) becomes

$$t_{1on} = \frac{2HB}{\frac{di_{fa}}{dt}} \qquad (27)$$

$$t_{1on} = \frac{2HBL_{fa}}{(\frac{V_{dc}}{2}) - V_a - i_{fa}R_{fa}} \qquad (28)$$

Applying the value of difa/dt in (27), t1on becomes

Similarly, when switch Q2 conducts, the voltage equation becomes

$$-\frac{V_{dc}}{2} - V_a - i_{fa}R_{fa} - L_{fa}\frac{di_{fa}}{dt} = 0 \qquad (29)$$

Thus

$$\frac{di_{fa}}{dt} = \frac{1}{L_{fa}}\left(-\frac{V_{dc}}{2} - V_a - i_{fa}R_{fa}\right) \qquad (30)$$

The negative rise of current through the period t′′ to t′′′ becomes

$$\frac{di_{fa}}{dt} = \frac{-2HB}{t_{1off}} \qquad (31)$$

Then off-time (t1off) becomes

$$t_{1off} = \frac{-2HB}{\frac{di_{fa}}{dt}} \qquad (32)$$

Applying the value of difa/dt in (32), t1off becomes

$$t_{1off} = \frac{-2HBL_{fa}}{\frac{V_{dc}}{2} + V_a + i_{fa}R_{fa}} \qquad (33)$$

$$f_c = \frac{1}{t_{1on}+t_{1off}} = \frac{1}{\frac{2HBL_{fa}}{\left(\frac{V_{dc}}{2}\right)-\left(V_a+i_{fa}R_{fa}\right)} + \frac{2HBL_{fa}}{\left(\frac{V_{dc}}{2}\right)+\left(V_a+i_{fa}R_{fa}\right)}}] \qquad (34)$$

The switching frequency (f c) is obtained by adding (28) and 33) (see (34)) Equation (35) can be obtained after simplifying (34) 2

$$f_c = \frac{1}{V_{dc}2HBL_{fa}}[\frac{{V_{dc}}^2}{4} - (V_a + i_{fa}R_{fa})^2] \qquad (35)$$

From (35), we can obtain the HB

$$HB = \frac{1}{V_{dc}2f_cL_{fa}}[\frac{{V_{dc}}^2}{4} - (V_a + i_{fa}R_{fa})^2] \qquad (36)$$

$$L_{sf}\frac{di_{ing}}{t_{1on}} = \left(\frac{V_{dc}}{2} - V_{scon} - i_{inj}R_{sf}\right) \qquad (37)$$

$$di_{inj} = di_i + di_{cf} \qquad (38)$$

where V a, Vdc, Lfa and ifa are the source voltage, DC-link voltage, coupling inductor and compensating current, respectively. For symmetrical operation of all three phases, it can be expected that HB profiles HBa, HBb, HBc will almost be same, but have a phase difference.

Analysis of switching dynamics in series converter

The primary function of a series converter is to suppress the sag/ swell, voltage harmonics and voltage unbalance from supply voltage. To accomplish this job accurately, the appropriate design of switching band is an important concern. The boundaries of switching band are created using a hysteresis band (h) as well as the reference voltage Vref, the lower and higher boundaries are defined as (Vref + h) and (Vref − h), respectively. To make the analysis easier, a single-phase series converter having a DC-link capacitor is taken into account as illustrated in Fig. 3c. A single-phase equivalent of series converter with exterior circuit parts is presented in Fig. 3d, where R g is the switching band resistor, added in series with filter capacitor to make the switching band more linear in compared to the switching band present during only capacitor filter, Vsir is the equivalent voltage source and Z p = (Rp + jwLp) is the equivalent impedance exterior to the series converter.

To originate a relation involving switching frequency along with some additional parameters, one period of switching action is demonstrated in Fig. 3d. Since both positive and negative reference voltages are same for band control operation, we take into account first positive reference voltage. When switch Q1a is on, a positive DC-link voltage +(Vdc/2) is applied over the filter elements. Applying Kirchhoff's voltage law and Kirchhoff's current law, the following equations are obtained

Injection current is slowly varied in nature in compared to the capacitor current. Thus variation of converter current is nearly equal to the variation in the capacitor current without losing accuracy. Thus (38) becomes

$$di_{inj} = di_{cf} \qquad (39)$$

Rearranging the aforementioned equation for calculation of length of positive slope as

$$t_{1on} = \frac{L_{sf}di_{cf}}{(\frac{V_{dc}}{2}) - V_{scon} - i_{inj}R_{sf}} \qquad (40)$$

Further a negative slope is obtained by making the switch Q2a on. This provides a converter output voltage as −(Vdc/2). The series converter voltage is discharged through capacitor current to reach the lower limit of (Vref − h). Similar to positive slope, the following equations are obtained for negative slope:

$$L_{sf}\frac{di_{ing}}{t_{1off}} = \left(\frac{V_{dc}}{2} + V_{scon} + i_{inj}R_{sf}\right) \qquad (41)$$

$$di_{inj} = -\,di_{cf} \qquad (42)$$

$$t_{1off} = \frac{L_{sf}di_{cf}}{\left(\frac{V_{dc}}{2}\right) + V_{scon} + i_{inj}R_{sf}} \qquad (43)$$

Thus the complete time length of one switching period can be figured out as

$$T_{sw} = t_{1on} + t_{1off} = \frac{4V_{dc}}{{V_{dc}}^2 - (2V_{scon} + 2\,i_{inj}R_{sf})^2}L_{sf}di_{cf} \qquad (44)$$

Modification in capacitor current dicf may be found from the capacitor dynamic equation

$$V_{scon} = \frac{1}{c_f}\int i_{cf}dt + R_g i_{cf} \qquad (45)$$

Differentiating and relocating the aforementioned equation, the variation of the capacitor current could be defined as

$$di_{cf} = \frac{1}{R_g}\left(dV_{scon} - \frac{i_{cf}t_{1on}}{c_f}\right) \qquad (46)$$

As series converter voltage Vscon is excellently tracking reference voltage Vscon_ref , the series converter voltage corresponding to reference voltage is Vscon = Vscon_ref. Due to a negligible voltage drop across the capacitor at high frequency, the variation of capacitor voltage is minimised. Thus

$$\begin{cases} dV_{scon} = (V_{scon_{ref}} + h) - \left(V_{scon_{ref}} - h\right) = 2HB \\ \frac{i_{cf}t_{1on}}{c_f} = dV_{cf} = 0 \end{cases} \qquad (47)$$

Substituting (47) into (46), the variation of capacitor current is procured as

$$di_{cf} = \frac{2HB}{R_g} \qquad (48)$$

Substituting (48) into (44), the time required for one switching period is obtained as

$$T_{sw} = \frac{L_{sf}8HBV_{dc}}{R_g[{V_{dc}}^2 - (2V_{scon} + 2\,i_{inj}R_{sf})^2} \qquad (49)$$

A fundamental component can only be assumed in the reference voltage and the switching frequency of the band controller can be expressed as

$$f_{sw} = \frac{R_g[{V_{dc}}^2 - 4\left(V_{scon} + i_{inj}R_{sf}\right)^2]}{L_{sf}8HBV_{dc}} \qquad (50)$$

A fundamental component can only be assumed in the reference voltage and the switching frequency of the band controller can be expressed asFrom (50), it is perceived that the switching frequency relies on R g/Lsf ratio, capacitor voltage, voltage drop in filter resistance, reference voltage and band (h). Simplifying (50) the HB for series converter is obtained by

$$HB = \frac{R_g}{V_{dc}2f_{sw}L_{sf}}\left[\frac{{V_{dc}}^2}{4} - \left(V_{scon} + i_{inj}R_{sf}\right)^2\right] \qquad (51)$$

SIMULATION RESULT AND DISCUSSION

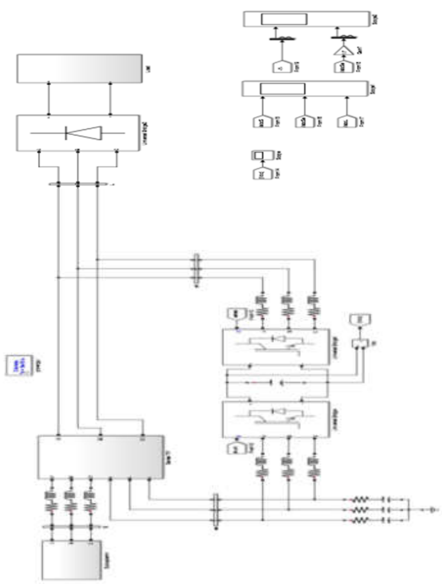
To verify the effectiveness of UPQC, the proposed control strategy has been tested using MATLAB/SIMULINK with system parameters given in Table 1. The three-phase UPQC system comprises of shunt and series converters with a common DC-link capacitor. A three-phase diode-rectifier bridge feeding RL load is used as a harmonic current producing load with a total harmonic distortion (THD) of 32.3%. For simulation analysis, some assumptions have been considered such as a step change of load at 0.15 s for transient performance, 20% of sag/swell creation between 0.12 and 0.18 s for four cycles, source voltage harmonic creation by adding fifth and seventh harmonics to the source voltage and voltage unbalance formation by varying phase-A and phase-C amplitudes up to ±20 % from its nominal value. Here we consider two different cases for analysing the performance of UPQC.

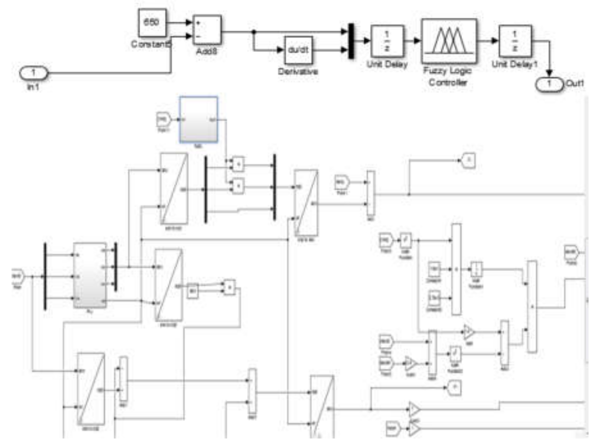
Table 1

System parameters

	Parameters	Notation	Value
source	voltage	V_{sabc}	360 V
	frequency	f	50 Hz
	resistor	R_s	1 Ω
	inductor	L_s	0.1 mH
load	diode rectifier		6-diode
	resistor	R_L	45 Ω
	inductor	L_L	35 mH
DC link	reference voltage	V_{dc_ref}	650 V
	capacitor	C_{dc}	4000 μF
shunt converter	interface inductor and resistor	(L_f, R_f)	2.5 mH and 0.5 Ω
	switching frequency	f_{sw}	10 kHz
series converter	AC filter inductor and capacitor	(R_{sf}, L_{sf}, C_f)	2 Ω, 2 mH and 6 μF
	switching band resistor	R_g	2 Ω
	injection transformer specification and inductance	L_j	7 : 1 turns ratio 4 mH

SIMULATION DAIGRAM



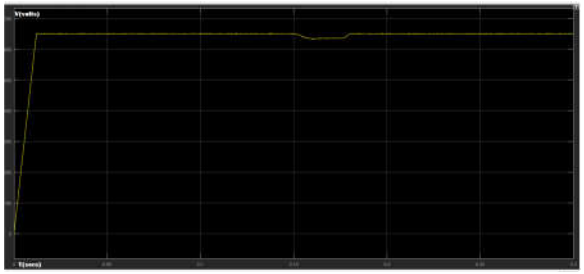


6.1 Case 1: DC-link voltage performance

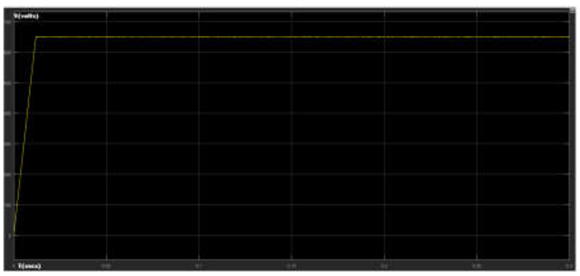
In this case, the performance comparison of NLSMC and fuzzy controllers for controlling the DC-link voltage of UPQC is considered. The comparison is based on the time required for stabilisation of DC-link voltage in the transient (load) and supply voltage disturbance conditions. The performance of the shunt converter of the UPQC for controlling the DC-link voltage with for a (R = 45 Ω, L = 35 mH) based on [19] and the values of KP and K I are about 0.248 and 0.065, respectively. It is observed from the figure that, in case of the PI controller, the shunt converter takes almost 0.06 s to stabilise the DC-link voltage at the initial condition. When the load changes from R = 45 Ω, L = 35 mH to R = 35 Ω, L = 25 mH with a step time of 0.15–0.3 s, it almost takes 0.07 s to reach a steady state with some overshoot and undershoot.

During the sag and swell conditions, the DC-link voltage falls down up to 560 and 570 V at 0.15 s from its reference value and takes 0.11 and 0.10 s, respectively, for stabilisation. In case of unbalance source voltage condition, the DC-link voltage slightly deviates from its reference value at 0.14 s and takes 0.05 s to stabilise. In case of the proposed fuzzy, the DC-link voltage stabilizes within 0.02 s at the initial stage, and at load transient condition, it takes about 0.04 s for stabilisation with low overshoot and low undershoot. In addition, the steady state ripples in DC-link voltage is negligible.

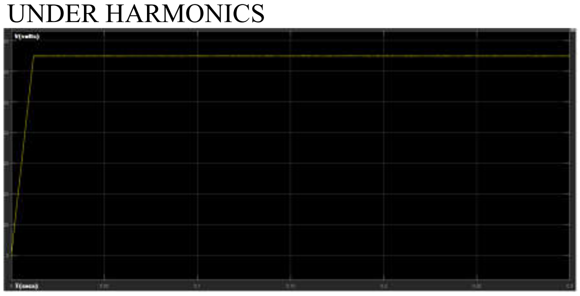
Thus, it helps in reduction of steady-state distortion in source current. When sag and swell occur in supply side, DC-link voltage falls down to 590 and 600 V, respectively, at 0.15 s and takes about 0.08 and 0.07 s to stable. In unbalanced case, DC-link voltage cannot deviates from its original position and always follows the reference value. Thus, the proposed fuzzy controller technique enhances the performance of UPQC. Table 2 gives a comparison of the DC-link performance for fuzzy and NLSMC controller schemes.



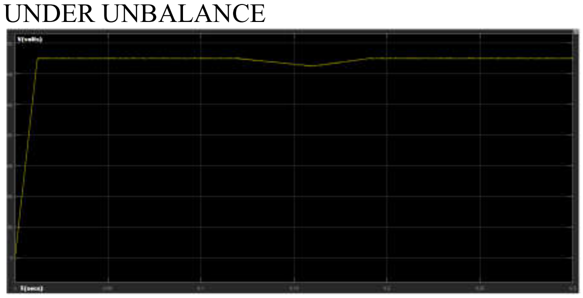
LOAD CHANGE



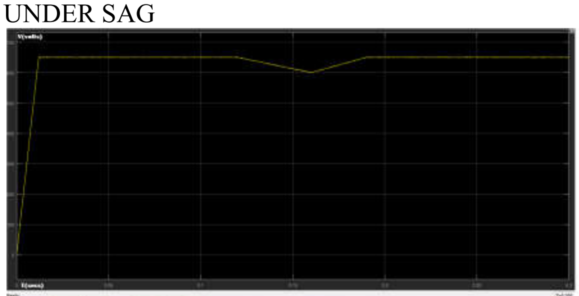
UNDER HARMONICS



UNDER UNBALANCE



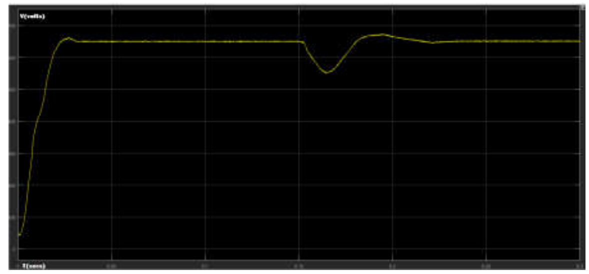
UNDER SAG



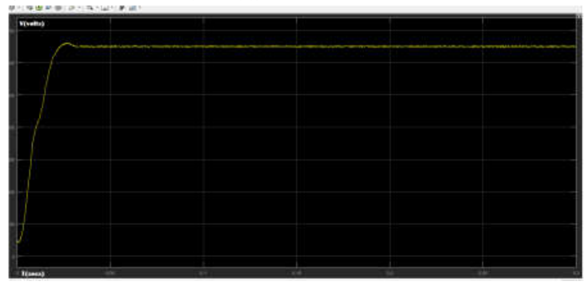
UNDER SWELL

Fig. 4 Performance of DC-link voltage under load change,harmonics,unbalance,sag,swell using FUZZY controllers

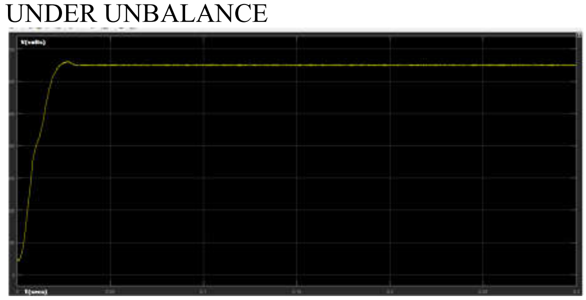
LOAD CHANGE



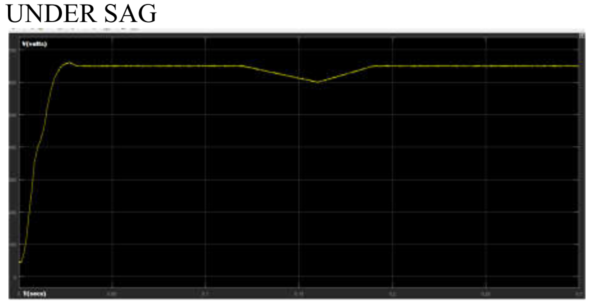
UNDER HARMONICS



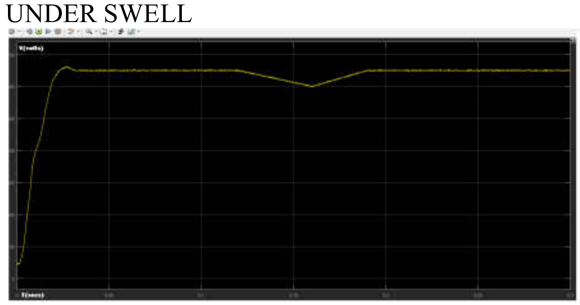
UNDER UNBALANCE



UNDER SAG



UNDER SWELL

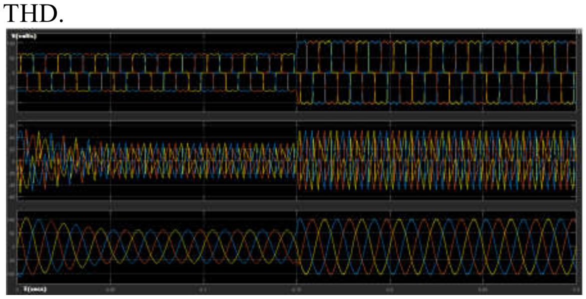


Performance of DC-link voltage under load change,harmonics,unbalance,sag,swell using NLSM controllers

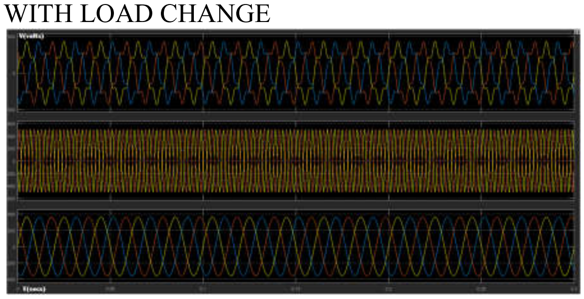
6.2 Case 2: Consideration of overall performance

In this section, we consider the overall operational performance of UPQC based on proposed control strategy. Fig. 4b shows the switching bands and switching patterns of both shunt and series converters of UPQC from top to bottom order.

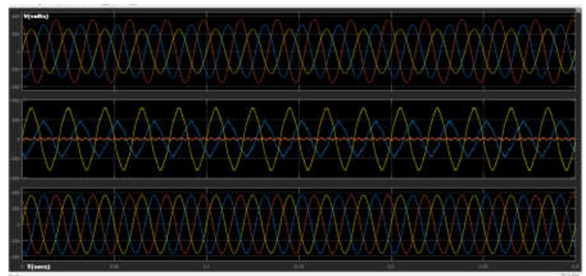
For shunt converter, the band violation is negligible during load changing conditions, thus, tracking the performance of compensating current is improved with greater reduction of ripples in the source current. In case of series converter, band violation is less during sag condition and band voltage is almost linear. Thus, it improves the tracking performance of compensating voltage, which in turn leads to better compensation capability to load voltage. The compensating current and voltage tracking performances of NLSM with fixed hysteresis controller The performance of shunt converter is tested in Fig. 5b with load changing conditions and it is found that proposed fuzzy shows better result as compared to NLSM with fixed hysteresis controller. The analysis is based on the THD.



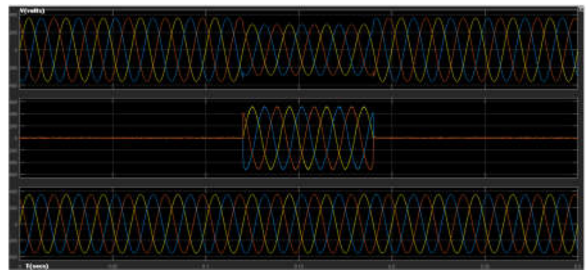
WITH LOAD CHANGE



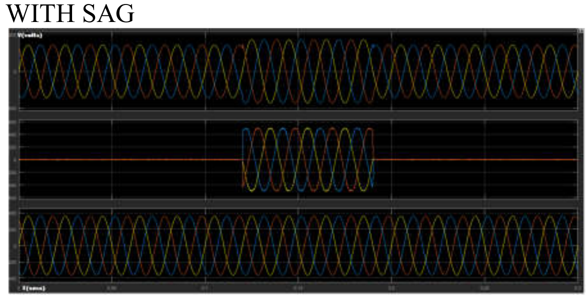
UNDER HARMONICS



UNBALANCE

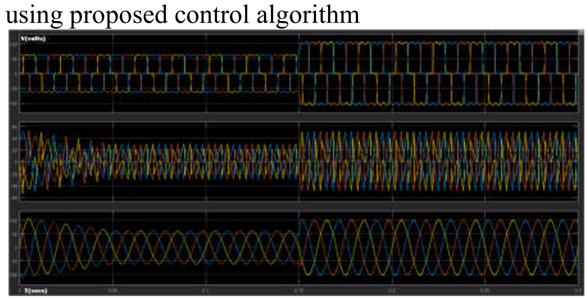


WITH SAG

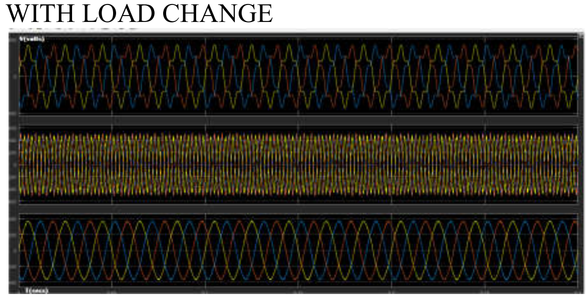


WITH SWELL

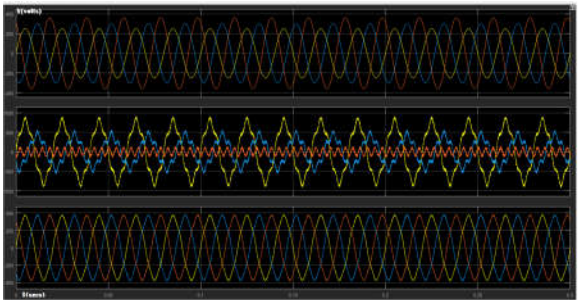
Performance of series converter of UPQC during load change,harmonics,unbalance and sag/swell condition using proposed control algorithm



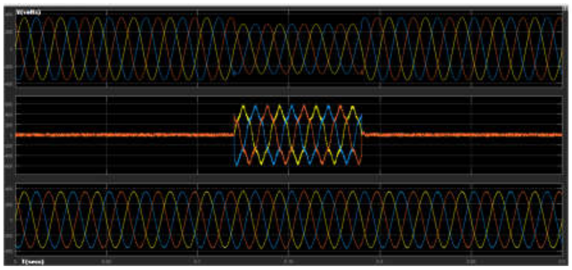
WITH LOAD CHANGE



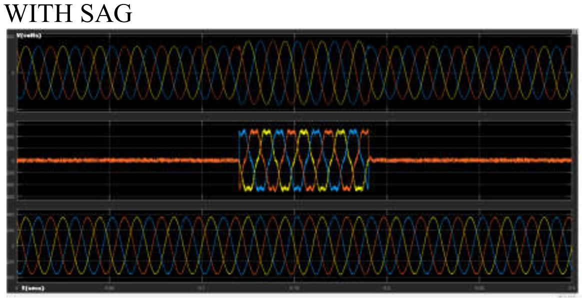
UNDER HARMONICS



UNBALANCE



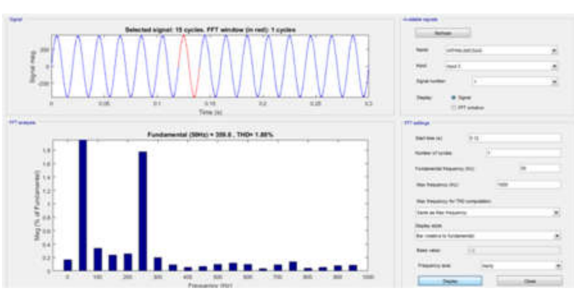
WITH SAG



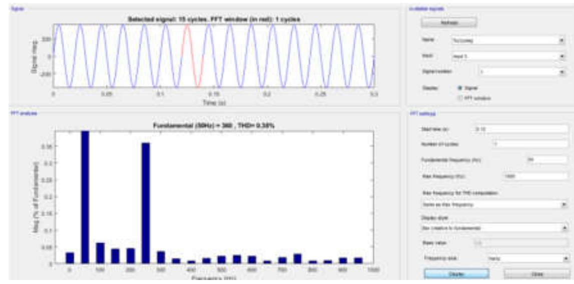
WITH SWELL

Performance of series converter of UPQC during load change,harmonics,unbalance and sag/swell condition using NLSM controller

Fig. 5 Simulation results for operating performance of the UPQC system



NLSM SAG THD



FUZZY SAG THD

According to Table 3, THD of the compensating voltage for sag and swell conditions are 1.88 %& 2.45 %respectively, in conventional controller, whereas in the case of proposed controller they are reduced to 0.38%& 0.38% respectively. Hence the proposed control strategy can enhance the compensation capability by reducing the amount of ripple in theNLSM with new switching dynamics are sequentially presented From the figure, it is clear that the proposed control strategy exhibits better tracking performance irrespective of disturbance occurring in load side or source side.NLSMC and fuzzy controllers for load transient, sag, swell and voltage unbalance conditions are given from top to compensation voltage. Fig. 5 shows the sag/swell voltage compensation performance, where the series converter is utilised to compensate the load voltage around its nominal value by proper injection of compensating voltage through series transformer. And it shows the compensation performance of series converter of UPQC for compensating harmonic voltage and unbalance source voltage. It is clear that, the proposed control strategy can satisfactorily eliminate all harmonics and unbalance present in the source voltage by injecting proper compensation voltage and makes the load voltage free from all such disturbances, which confirms the superiority of the proposed control strategy.

Table 4

Compensating voltage THD Comparison for conventional and proposed control method

Different conditions	Conventional NLSM	Proposed control method,%
THD during sag condition	1.88%	0.38%
THD during swell condition	2.48%	0.38%

CONCLUSION

A novel NLSMC technique along with new switching dynamics control strategy for UPQC is proposed in this paper to improve the PQ problems in power distribution network. It is observed from both simulation and experimental studies that, the fuzzy controller technique is superior to NLSM controller for controlling the DC-link voltage of UPQC, as it delivers less overshoot and less settling time for stabilising the DC-link voltage during occurrence of load transient, voltage sag/swell, voltage unbalance and voltage interruptions in the power distribution network. The performance of UPQC mainly depends upon how accurately and how quickly reference signals are derived. The proposed switching dynamics control strategy generates the HB more accurately and makes the band calculation simpler. Consequently, this control strategy can overcome drawbacks of band violation and switching losses occurring in the fixed hysteresis band, in the presence of load as well as source perturbations. Therefore, the tracking performance of UPQC is improved, which drastically reduces the switching ripples present in the compensating voltage and source current. With the aforementioned views, it can be realised that the proposed fuzzy controller with switching dynamic for HB control strategy can enhance the performance of UPQC during power system dynamic conditions by eliminating PQ problems such as current/voltage harmonics, voltage sag/swell, voltage unbalance and voltage interruptions.

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