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Improvement of PQ with PI and IT1FLC DSTATCOM in Distribution Network

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ABSTRACT

The major causes for power quality issues are the ever increasing non-linear commercial, hospital loads and industrial loads. In this scenario the hospital loads which include different non-linear, unbalanced and sensitive loads to the grid should be prioritized. Major power quality issues are caused due to these load specifications in local distribution network. And here harmonic injection and imbalance of reactive power occurs due to its rapid spread in divergence. To mitigate the harmonics, compensate the neutral current and balancing the load as well as reactive power, DSTATCOM is introduced. The method entails a PI controller and an Interval-1 Fuzzy Logic Controller to boost the PQ in the local distribution grid. Initially the system model is studied then different loads connected to the grid are analyzed. The standard DSTATCOM employed as a mitigating device follows the earlier design procedure. In this work control algorithm required for simulation of DSTATCOM is formulated and obtained results could be analyzed. This work mainly focused on the efficient operation of the distribution network suffering from the high disturbances caused by the sensitive hospital loads.

INDEX TERMS *Distribution STATCOM, Distribution STATCOM, interval type-1 fuzzy logic controller (IT1FLC), PI controller, power quality (PQ).*

INTRODUCTION

The voltage and current ratios in power distribution grid are aimed to be sinusoidal. The rising use of non-linear load as a result of new technologies creates a serious power quality issue. Hospital loads put a burden on the system by harming devices, enabling current to pass through neutral conductors, producing waveform distortion, overheating, and losing power factor. Light, heavy, non-linear, linear, balanced, and unbalanced models are all found in these local hospitals. In fact, the large bulk of them are extremely sensitive and digitally controlled. SMPS are necessary for digital control of a load and they are less sensitive to PQ. Major power polluters include, equipment in Critical Care Unit (CCU) facilities, magnetic resonance imaging (MRI) scan machines, X-ray machines, lighting loads in operating rooms, computed tomography (CT), and equipment in Intensive Care Unit (ICU) facilities. The operation of these sorts of loads is unavoidable due to their extreme sensitivity, which results in harm or loss of human life if they are disconnected.

The majority of commercial utility loads are hefty and inductive, causing voltage sag and swell during load switching. CPDs (Custom Power Devices) can help to reduce these PQ problems. To improve PQ, voltage or current, or both, are added into the system at the point of common coupling (PCC). The terminal voltage may be controlled as a result, resulting in a significant power factor. CPDs include the Dynamic Voltage Restorer (DVR), DSTATCOM (Distribution Static Compensator) and others. DSTATCOM enhances performance and dependability by supplying the required reactive power. When large loads are suddenly removed, the DSTATCOM provides better voltage support than SVC and other CPDs. Over a non- linear operational range, the DSTATCOM completely changes its output current of AC system voltage. The DSTATCOM has a near-instantaneous response time and can readily interface with energy storage devices such as massive capacitors, batteries, and Fuel Cells (FC). DSTATCOM's control algorithms come in a variety of flavours. ISCT (Instantaneous Symmetrical Component Theory), SRFT (Synchronous Reference Frame Theory), and IRPT (Instantaneous Reactive Power Theory) are the most widely employed theories. The Euclidean Direction Search technique (EDST) is used to manage VSC, combined with a zig-zag transformer for neutral current compensation. As an improvement to ANN, the Chebyshev functional expansion based artificial neural network (ChANN) algorithm was developed. For effective DSTATCOM control, operators other than traditional PI controllers are favoured. The Total Harmonic Distortion values of Artificial Intelligence-based controllers such as the Fuzzy Logic Controller (FLC) and Artificial Neural Network (ANN) are compared to the PI controller. In the IT1FLC, the membership functions are represented as an interval with Lower(L) and Upper (U) functions. For effective DSTATCOM control, controllers other than traditional PI controllers are recommended. The Total Harmonic Distortion values of AI-based controllers such as the Fuzzy Logic Controller (FLC) and Artificial Neural Network (ANN) are matched to the PI controller. As a result, an interval determines the range of incomplete data. This allows for more accurate result than other AI techniques. And IT1FLC provides precise system control with low THD.

The following are the three main contributions of our work:

(1) An IT1FLC with RLS filter-based DSTATCOM was designed to enhance PQ in the local distribution network (LDN).

(2) A thorough simulation of the LDN's power quality with and without the proposed DSTATCOM setup.

(3) In terms of harmonic spectrum, the stated RLS filter based IT1FLC controlled DSTATCOM is determined by the standard T1FLC, PIcontrolled DSTATCOM.

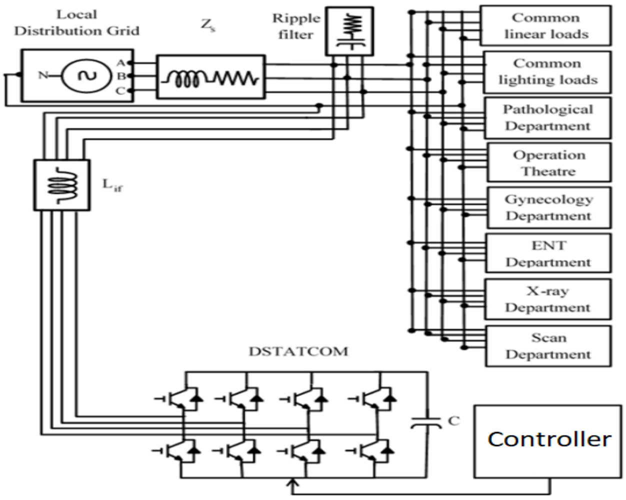

Fig1. Structure of proposed DSTATCOM with interval Type-1 fuzzy logic controller.

The study's system configuration model is discussed. Following that, a detailed analysis of the system's connected

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loads is provided. The design procedure for DSTATCOM, which will be used as a mitigating device, follows. The control algorithm formulation for the DSTATCOM operation is in detail and going thorough examination of the simulation's outcomes. The proposed technique is also analyzed and compared to others of its kind.

SYSTEM CONFIGURATION

A three-phase four-wire local distribution network (LDN) is updated with sensitive hospital loads, as shown in Fig1. The research focuses on the loads at the medical facility, as well as the RLS filter and IT1FLC based DC voltage controller. Real-time data from a hospital is used during load modelling work. Combination of linear ,heavy, non-linear, and unbalanced loads the proposed load model involves at various times. The LDN's 11 kV capacity is connected to the hospital's 415 V loads through a step-down transformer. A DSTATCOM is shunt-connected to the LDN and assists with current harmonic mitigation, neutral current compensation, reactive power compensation, and load balancing. DSTATCOM employs the IT1FLC as a reference current generator, and that current eliminates the reactive component of the load. As a result, the source current component is reduced to real terms only, removing the need for the reactive terms. The DSTATCOM relieves the generator's reactive power burden as a result of this.

SYSTEM MODELING

The importance of load modeling in this proposed effort cannot be overstated. In the hospital, there are linear, non-linear, balanced, sensitive and unbalanced loads. To connect a number of DC loads to the AC supply, a rectifier is used. The hospital loads are extremely sensitive to PQ issues. The proposed system accounts for a wide range of medical pressures. ICU, pathology, operating theater, ENT, gynecological, X-ray, scan centers, and so on are just a few of the departments. The total load in the system is influenced by peak loads, critical loads, continuous operation, and seasonal loads.

DC BUS VOLTAGE

Typically, the DC voltage Vdc value should be greater than the amplitude of the AC voltage. As a result, Vdc is calculated using the voltage of PCC at LDG. The Vdc is determined from (1)[2]

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}mi} \qquad (1)$$

where m is the modulation index, which is one, and VLL is the DSTATCOM's line-to-line ac voltage. The obtained Vdc value is 677 V, whereas the V_{LL} value is 415 V. As a result, the DC voltage reference V_{dc}^* is set to 700 V.

DC BUS CAPACITOR

The DC bus capacitor is a crucial component that is designed to accommodate variations in DC voltage. The capacitor for the DC bus (C_{dc}) is made of (2) [2]

$$\frac{1}{2}C_{dc}[(V_{dc}^*)^2-(V_{dc})^2]=k3V_{ph}(aI)t \qquad (2)$$

Where, V_{ph} is the phase voltage and V_{ph} = 240 V, I is the phase current, t is the DC bus voltage recovery time and t=0.04s, an is the overload factor and a = 1.2, and k = 0.1. The value of C_{dc} is determined and estimated to be around 10000 F.

AC INDUCTOR

The ripple current and switching frequency are used to construct the AC inductor. The AC inductor is estimated from (3) [2]

$$L_{if} = (\sqrt{3} * m * V_{dc}) / (12 * a * f_{sw} * i_{cr}) \qquad (3)$$

Where, f_{sw} is the switching frequency, which is set at 10 kHz. The AC inductor value is calculated to be 2.25 mH.

RIPPLE FILTER

A capacitor in series with a resistor is used to create the ripple filter. A first-order high pass filter is modelled and utilized to filter the PCC voltage's high-frequency signals.

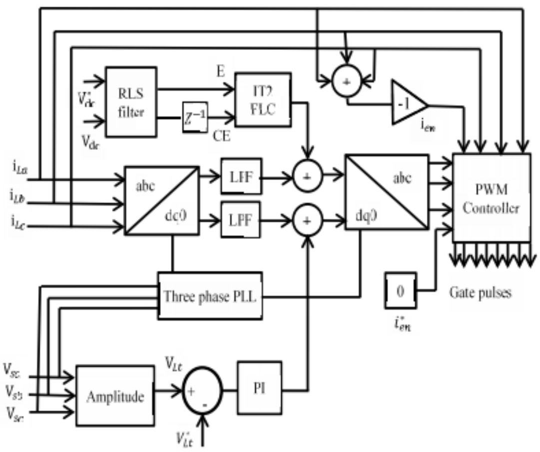

Fig2: IT1FLC control algorithm-based Distribution Static Compensator with RLS filter.

The values of the capacitor and resistor are determined from equations (4) to (5) [2].

$$R_{rf} * C_{rf} \le T_s \qquad (4)$$

If the switching time is low,

$$R_{rf} * C_{rf} \le 1/4 f_s \qquad (5)$$

The resistance value for the filter is set to 5, and the capacitance is calculated using equation (6) [2].

$$5 * C_{rf} \le 1/4 * 10000 \qquad (6)$$

CONTROL ALGORITHM

The proposed DSTATCOM uses an IT1FLC and PI controller based SRF to provide a reference current signal, and the associated structure is depicted in Fig2. The operation of the SRF theory begins with the transformation of voltages and currents into the α − β −0 axis. The d − q axis denotes the d-direct and q-quadrature axes, respectively.

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$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (7)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (8)$$

The angle is calculated using the Phase Locked Loop (PLL) in relation to the axis. A reference d q frame is created using this method. The transformation from α - β - 0 to d - q - 0 the frame is described as follows:

$$\begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \qquad (9)$$

The sum of their respective DC and AC components is given as the d-q component of current.

$$i_d = i_{dDC} + i_{dAC} \qquad (10)$$

$$i_q = i_{qDC} + i_{qAC} \qquad (11)$$

The current generated by the reference source is generated by (12)

$$i_d^* = i_{dDC} + i_{d2} \qquad (12)$$

where i_{d2} is the output of the DC voltage controller's IT1FLC.

At the PCC, there should be no zero-sequence components, and the reference source current and voltage should be in phase. The d-q-0 frame is turned back to the α − β −0 axis using reverse transformation.

$$\begin{bmatrix} i_{s0}{}^* \\ i_{s\alpha}{}^* \\ i_{s\beta}{}^* \end{bmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{bmatrix} 0 \\ i^*{}_d \\ 0 \end{bmatrix} \qquad (13)$$

The source current is reversed and converted from α − β − 0 frame to a-b-c frame using the reverse transformation.

$$\begin{bmatrix} i_{sa}{}^* \\ i_{sb}{}^* \\ i_{sc}{}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 0 & 1 & 0 \\ 0 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ 0 & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{bmatrix} i_{s0}{}^* \\ i_{s\alpha}{}^* \\ i_{s\beta}{}^* \end{bmatrix} \qquad (14)$$

The performance of the IT1FLC and PI controller as a DC voltage controller. The AC terminal voltage (V_{Lt}) at the PCC is adjusted with regard to the reference terminal voltage (V_{Lt}) using the PI controller. The PI controller's output is the reactive component of current. This aids in the regulation of the PCC's AC voltage at LDG. The AC terminal voltage (V_{Lt}) at the PCC is computed using the three phases' AC source voltages (V_{sa}, V_{sb}, and V_{sc}) as follows:

$$V_{Lt} = \sqrt{\frac{2}{3}}\sqrt{(V^2{}_{sa} + V^2{}_{sb} + V^2{}_{sc})} \qquad (15)$$

$$i_{qr(n)} = i_{qr(n-1)} + K_{pq}(V_{te(n)} - V_{te(n-1)}) + K_{iq}V_{te(n)} \qquad (16)$$

Where $V_{te}(n) = V_{Lt}$ V_{Lt} (n) is the terminal voltage error, n is the number of samples, and K_{pq},K_{iq} are the gains of Proportional-Integral controller.

In the quadrature axis, the reference current is determined as,

$$i_q^* = i_{qDC} + i_{qr} \qquad (17)$$

This is again transformed to α − β − 0 axis as follows,

$$\begin{bmatrix} i_{s0}{}^* \\ i_{s\alpha}{}^* \\ i_{s\beta}{}^* \end{bmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{bmatrix} 0 \\ i_d{}^* \\ i_q{}^* \end{bmatrix} \qquad (18)$$

The source current is reversed and converted from α - β -0 frame to a-b-c frame using the reverse transformation.

$$\begin{bmatrix} i_{sa}{}^* \\ i_{sb}{}^* \\ i_{sc}{}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 0 & 1 & 0 \\ 0 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ 0 & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{bmatrix} i_{s0}{}^* \\ i_{s\alpha}{}^* \\ i_{s\beta}{}^* \end{bmatrix} \qquad (19)$$

The reference current's reference value is zero(0). This aids in the load-neutral current's neutralisation. Between the extracted current and the reference currents, a comparison is done. The PI controller is in charge of amplification of the fault. This is in contrast to the triangular carrier signal. This aids in the generation of gate pulses for VSC's six switches. The gate pulses for DSTATCOM's fourth leg are created using a comparison of the reference neutral current (i^*_{en}) and the extracted neutral current (i_{en}). Equations (20) and (21) are used to arrive at these results.

$$i^*{}_{en} = 0 \qquad (20)$$

$$i_{en} = -(i_{ea} + i_{eb} + i_{ec}) \qquad (21)$$

RLS FILTER

For the specified reference signal and actual signal, the RLS filter aids in the computation of the output is in its

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error, form of filter, and weights [9]. The filter's least square coefficients are estimated using the beginning circumstances that have been determined. The filter is continually updated as new data from the previous approximated data becomes available. This filter's main aim function f(n) is to reduce the error [11].

$$f(n) = \sum_{k=1}^{n} \eta_n(n)e^2(n) \quad (22)$$

where e (n) stands for the error, n(n) denotes the weighting factor, and n stands for the count of iterations.
From the equation, the error is computed (23),

$$e(n) = V^*{}_{dc}(n) - V_{dc}(n) = V^*{}_{dc}(n) - w^T(n-1)x(n) \quad (23)$$

V^*_{dc} is the DC estimated voltage, i.e., the actual DC voltage, and Vdc is the reference DC voltage.

$$x(n) = [x(n)\ \ x(n-1)\ \ \cdots\cdots\ \ x(n-M+1)]^T \quad (24)$$

$$w(n) = [w_1(n)\ \ w_2(n)\ \ \cdots\cdots\ \ w_M(n)]^T \quad (25)$$

where, M is the length of the vector.
Below equation is Recursive Least Filter weight after updation:

$$k(n) = \frac{P(n-1)x(n)}{\lambda + x^T(n)P(n-1)(n)} \quad (26)$$

$$w(n) = w(n-1) + k(n)e(n) \quad (27)$$

$$P(n) = \frac{1}{\lambda}\left[P(n-1) - k(n)x^T(n)P(n-1)\right] \quad (28)$$

where k (n) is the kalman gain vector, P (n) is the inverse of the input correlation matrix, and is the forgetting factor The forgetting factor remains between 0 and 1. When the value of is close to 1, the filter achieves quick convergence. The value can be computed using the following formula:

$$1 - \frac{1}{2L} < \lambda < 1 \quad (29)$$

Where, L stands for length of the filter.

TYPE 1 FUZZY LOGIC CONTROLLER

When compared to conventional methods, the FLC provides superior performance, less complexity, and more precise control. The variables in the input are error (E) and Change in the Error (CE), as well as the output. Equations (30) and (31) are used to calculate the CE.

$$E(t) = V^*{}_{dc} - V_{dc(t)} \quad (30)$$

$$CE(t) = E(t) - E(t-1) \quad (31)$$

where t denotes the time sample In Fig3, the E, CE, and output are split into five fuzzy sets, and the Membership Functions (MFs) are displayed. In this study, triangular Membership Functions are chosen for the Type-1 Fuzzy Logic Controller DC voltage controller. When compared to other types of MFs, triangular MFs provide a faster settling time, reduced overshoot, a simpler design, and more precise output .NT (Neutral), AH (Appreciate High), AT (Appreciate Tiny), DT (Depreciate Tiny), and DH (Depreciate High) are the Membership Functions. In the defuzzifier module, the centroid approach is used to estimate the output of this T1FLC. The output is fed into the current regulator, which extracts signals as reference current. The result is i_{d2}, which employs the rule.

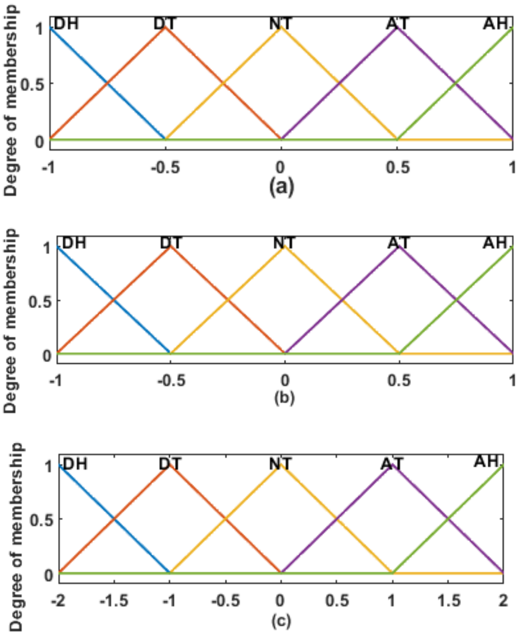

Fig3. MF's of Interval Type-1 Fuzzy Logic Controller as DC voltage regulator (a) Error (b) Change in error (c) output.

TABLE 1. Interval Type -1 Fuzzy Logic Controller Rule Base.

E / CE	DH	DT	NT	AT	AH
DH	NT	NT	AH	AH	AH
DT	NT	NT	AT	AT	AT
NT	AT	NT	NT	NT	DT
PS	DT	DT	DT	NT	NT
AH	DH	DH	DH	NT	NT

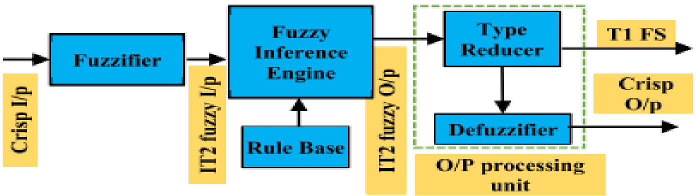

Fig4. Working Scheme for Interval Type 1 fuzzy logic controller

SIMULATION RESULTS

The study examines and evaluates the impact of power quality concerns at hospitals caused by sensitive loads, as well as an unique strategy for improving power quality and making the distribution network more steady and reliable . Power Quality is improved by using an Interval Type-1 Fuzzy Logic Controller based DSTATCOM in connection with an RLS filter, which improves Total Harmonic Distortion(THD).

Without Distribution Static Compensator, the system is initially run , and parameters such as load current, source current, load voltage, and source voltage waveforms are acquired and displayed in Fig5.By connecting across the load, system is simulated with Distribution Static Compensator connected across the load, yielding DSTATCOM voltage and currents in addition to the so load as well as souce waveforms. The harmonic spectrum for both scenarios is obtained during peak load operation in order to estimate the compute of power quality. Subsections A and B deal with the detailed consideration of both cases.

PERFORMANCE ANALYSIS OF LDG WITHOUT DSTATCOM

In general, hospitals are made up of a variety of sensitive loads that are connected in 1-phase as well as three-phase connections with a neutral conductor. The loads are customized using the datasheet for load equipment in question. The 108-kW linear and lighting load, which consists of a variety of 12 W, 16 W, 32 W, 36 W, and 40 W LED bulbs, is regarded as a continuous working load. This covers emergency rooms like Intensive Care Unit (ICU) and Critical Care Unit (CCU) loads. These loads are not only delicate, but potentially life-threatening. Because the system's running duration is primarily from 5 a.m. to 11:30 a.m., the PD and OT loads are coupled for 0.20 to 0.40 seconds. V_s stands for the source voltage, I_s stands for the source current, I_{sn} stands for the source side contains neutral current, V_l stands for the load voltage, I_l stands for the load current, and I_{ln} stands for the neutral current on the load side in Fig6. The massive, unstable, and non-linear loads are operated between 0.40 seconds and 0.60 seconds. This causes significant current harmonics and, as a result, source current waveform distortion. Despite the fact that the whole system contains both linear and non-linear, stable and unstabled loads, the magnitude of the load disturbance ranges from 0.4 to 0.5 seconds. As the ENTD and GD loads are separated from 0.50 s to 0.60 s, the disturbance caused by non-linear loads diminishes marginally, while power consumption drops slightly. All heavy unbalanced loads from ENTD, XD, GD, SD, OT, and PD are turned off after 0.60s, signaling the end of the day. The system is still connected to the other linear continuously driven loads. The SD and XD loads use a lot of current, which causes an unbalance and introduces harmonics into the system (see Fig5). The source current is imbalanced due to the operation of non-linear loads, resulting in distortions and greater THD**.** Moreover, the X-ray and scan departments have large capacity loads, consuming several kW of power. In the system,the massive flow of neutral is aided by this. At 0.20 s, the neutral current flow begins to increase, and at 0.40 s, over 50 Ampheres of current flows through it. This shows that the system is connected to the entire hospital load, resulting in peak power consumption.

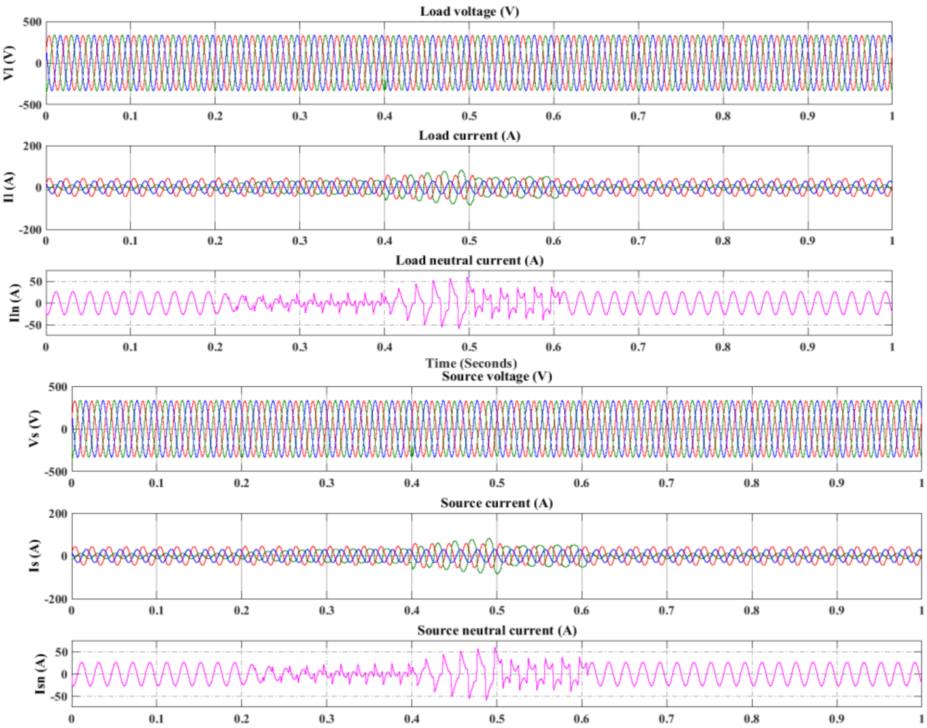

Fig5.Source and Load current waveforms of the medical loads connected to Distribution Network without DSTATCOM.

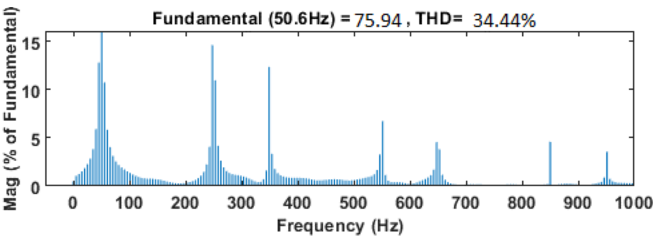

Fig6. Phase B harmonic spectrum

PERFORMANCE ANALYSIS OF THE SYSTEM WITH DSTATCOM

Individual 1-phase and 3-phase loads are coupled to various light and heavy loads. This results in severe load imbalance, non-linear load harmonics, and a large quantity of current in the neutral conductor. DSTATCOM is used to address these power quality issues. The controllers utilised in the DSTATCOM to control DC voltage are the PI controller, T1FLC The execution of the medical loads connected to the distribution network system with Distribution Static Compensator and Interval Type-1 Fuzzy Logic Controller is shown in Fig 7 and 8. The DSTATCOM voltage is V_{dst}, the DSTATCOM current is I_{dst}, and the compensating neutral current from DSTATCOM is I_{dstn}. By injecting the necessary current (I_{dst}), the DSTATCOM adjusts for power quality concerns. The source current (I_s) becomes sinusoidal and balanced as a result of the compensating neutral current. With an IT2FLC-based DSTATCOM, Vdc indicates the DC voltage. The IT2FLC delivers more precise control. During variable load situations, the IT2FLC assists in keeping the Vdc close to the reference DC voltage of 700 V. The Recursive Least Square(RLS) filter gives its error as squared and error output with filtered in a recursive

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manner to produce the best possible result. The forgetting factor aids in the achievement of rapid convergence. It also operates at a rapid rate and consistently functions even when the difference between the reference DC voltage and the actual DC voltage is quite small. The RLS filter's feature improves DSTATCOM's performance.

The RLS filter has a higher level of precision than the traditional LPF. One of the inputs to IT1FLC is the accurate error output from the Recursive Least Square filter. The other input for IT1FLC is the change in error. The CE is precise because the RLS filter's error output is accurate. The performance of IT1FLC in managing

the DC voltage is exact and faultless thanks to the RLS filter. The Vdc waveform depicted in Fig8 can be used to achieve this.

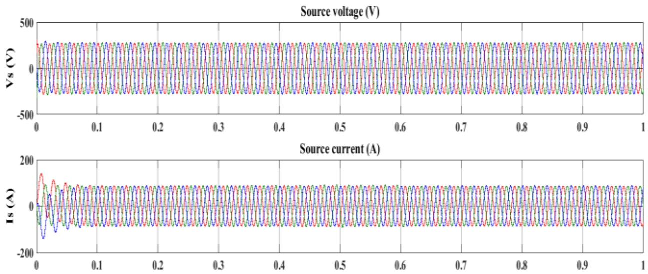

Fig7:Source current waveforms of hospital loads connected to Distribution network with DSTATCOM

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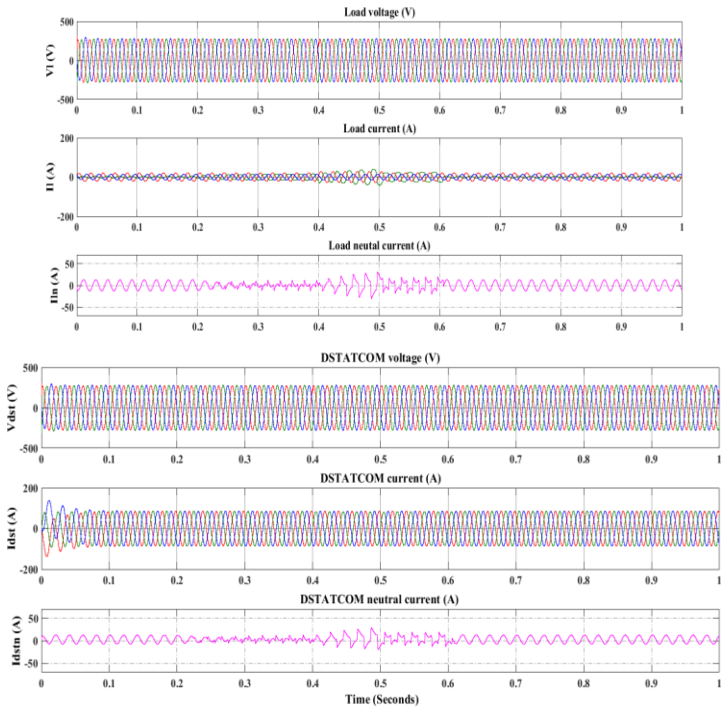


Fig8. Load current waveforms of the hospital loads connected to Distribution network with DSTATCOM.

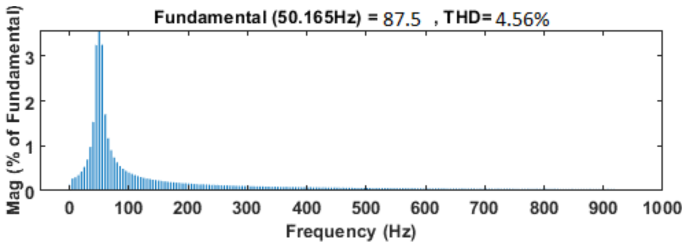
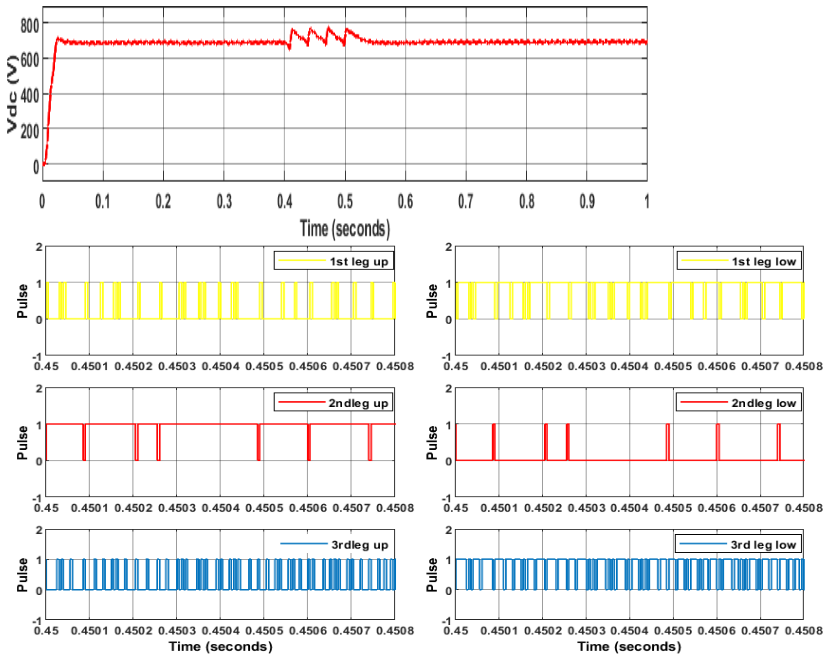


Fig9. Source current harmonic spectrum with DSTATCOM.

Fig10. Generating of Switching Pulses for DSTATCOM switches.

CONCLUSION

This study validated the performance of IT1FLC-based DSTATCOM, and the results show that it is successful when delicate loads are linked to the network. It has been shown useful in suppressing harmonics due to its proficient control behaviour and quick response. The simulated results and tabulation show that the proposed controller outperforms traditional controllers. The productive operation of the local distribution network with



delicate loads, which are a origin of disruptions from a generation standpoint, was the focus of this paper. The use of an IT1FLC-based DSTATCOM in the process decreases total harmonic distortion widely, and the RLS filter aids in fine-tuning it to acute levels. Additionally, lowering the harmonic value of currents at the source side aids in a significant reduction in total harmonic distortion and offers a much improved outline of voltage and current waveforms. The fourth leg of VSC helps to mitigate neutral current flow caused by imbalanced loads.

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