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Optimal Voltage Control Scheme on an Observer-Based For Three-Phase Ups Systems by Using Fuzzy

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Abstract

A simple optimum voltage control method is proposed in this paper for three phase uninterruptible power supply systems based on fuzzy control. Moreover, the optimal load current observer is employed to optimize system cost and reliability. The previous term is designed to make the system errors converge to zero, whereas the latter term is applied to compensate for the system uncertainties then the closed loop stability of an observer based optimal voltage control law is mathematically proven by showing that the whole states of the increased observer based system errors exponentially converge to zero. Specially, fuzzy control techniques are terribly interesting for a wide range of applicable fields allowing regulation of voltage profiles handling uncertainty and inexact information. The designing of the proposed controller is validated through simulations on MATLAB/Simulink and experiments on a prototype 600-VA test bed with a TMS320LF28335 DSP. Here fuzzy management is used compared to other controllers. Finally, the comparative results for the proposed scheme and therefore the conventional feedback linearization control theme are given to demonstrate that the proposed algorithm achieves an excellent performance like fast transient response, small steady state error, and low total harmonic distortion under load step change, unbalanced load and nonlinear load with the parameter variations.

Keywords - Optimal load current observer, optimal voltage control, Three phase inverter, total harmonic distortion (THD), uninterruptible power supply (UPS).

I. INTRODUCTION

As a UPS differs from an auxiliary or emergency power system or stand by generator in that it will provide near instantaneous protection from input power interruptions, by supplying energy which is stored in batteries, super capacitors or flywheels. Recently, the importance of the UPS systems has been intensified more and more due to the increase of sensitive and critical applications such as communication systems, medical equipment, semiconductor manufacturing systems, and data processing systems.

Uninterruptible power supply (UPS) systems supply emergency power in case of utility power failures. These applications require clean power and high reliability regardless of the electric power failures and distorted utility supply voltage. Thus, the performance of the UPS systems is usually evaluated in terms of the total harmonic distortion (THD) of the output voltage and the transient/steady state responses regardless of the load conditions: load step change, linear load and nonlinear load. Here we are using fuzzy control compared to other controllers to improve the aforementioned performance indexes, a number of control algorithms have been proposed such as fuzzy control, H∞ loop-shaping control, model predictive control, deadbeat control, sliding-mode control, repetitive control, adaptive control, and feedback linearization control (FLC). In, the H∞ loop-shaping control scheme is described and implemented on a single-phase inverter, which has a simple structure and is robust against model uncertainties.

Optimal voltage control scheme for three-phase UPS systems has a good voltage regulation capability such as fast transient behavior, small steady-state error. This has low THD under various load conditions such as load step change, unbalanced load and nonlinear load in the existence of the parameter variations. The optimal control has good properties such as enough gain and phase margin, robustness to uncertainties, good tolerance of nonlinearities. The former term is designed to make the system errors converge to zero, and the latter term is applied to estimate the system uncertainties.

The Lyapunov theorem is used to analyze the stability of the system. Specially, this paper proves the closed loop stability of an observer based optimal voltage control law by showing that the system errors exponentially converge to zero. Moreover, the proposed control law can be systematically designed taking into consideration a tradeoff between control input magnitude and tracking error unlike previous algorithms.

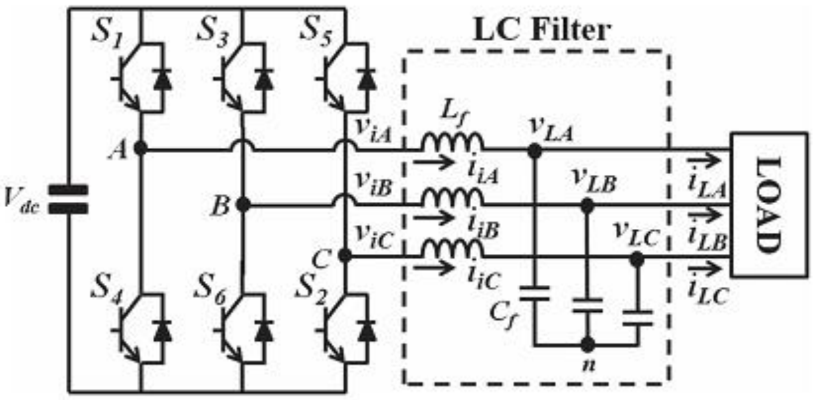

Fig.1. Three-phase inverter with an LC filter for a UPS system.

II. SYSTEM DESCRIPTION AND PROBLEM FORMULATION

The three-phase UPS system with an LC filter is shown in Fig. 1, which is composed of a dc-link voltage (V_{dc}), a three phase pulse width modulation (PWM) inverter ($S_1 \sim S_6$), an output LC filter (L_f, C_f), and a three phase load (e.g., linear or nonlinear load). Based on Fig. 1, the dynamic model of a three phase inverter can be derived in a d−q synchronous reference frame as follows:

$$\begin{cases} \dot{i}_{id} = \omega i_{iq} + k_2 v_{id} - k_2 v_{Ld}, \quad \dot{v}_{Ld} = \omega v_{Lq} + k_1 i_{id} - k_1 i_{Ld} \\ \dot{i}_{iq} = -\omega i_{id} + k_2 v_{iq} - k_2 v_{Lq}, \quad \dot{v}_{Lq} = -\omega v_{Ld} + k_1 i_{iq} - k_1 i_{Lq} \end{cases} \quad (1)$$

where $k_1 = 1/C_f$, and $k_2 = 1/L_f$. In system model (1), v_{Ld}, v_{Lq}, i_{id}, and i_{iq} are the state variables, v_{id} and v_{iq} are the control inputs. In this scheme, the assumption is made to construct the optimal voltage controller and optimal load current observer as follows

1) The load currents (i_{Ld} and i_{Lq}) are unknown and vary very slowly during the sampling period.

III. PROPOSED OPTIMAL VOLTAGE CONTROLLER DESIGN AND STABILITY ANALYSIS

A. Optimal Voltage Controller Design

A optimal voltage controller is proposed for system (1). First, let us define the d − q-axis inverter current references (i^*_{id}, i^*_{iq}) as

$$i^*_{id} = i_{Ld} - \frac{1}{k_1}\omega v^*_{Lq}, i^*_{iq} = i_{Lq} + \frac{1}{k_1}\omega v^*_{Ld} \quad (2)$$

Then, the error values of the load voltages and inverter currents are set as

$$\begin{aligned} &v_{de} = v_{Ld} - v^*_{Ld}\,, v_{qe} = v_{Lq} - v^*_{Lq} \\ &i_{de} = i_{id} - i^*_{id},\ i_{qe} = i_{iq} - i^*_{id} \end{aligned} \quad (3)$$

Therefore, system model (1) can be transformed into the following error dynamics:

$$\dot{x} = Ax + B(u + u_d) \tag{4}$$

where x = [v_{de} v_{qe} i_{de} i_{qe}] ^{T}, u = [v_{id} v_{iq}] ^{T}, u_d = [d_d d_q] ^{T}

$$A = \begin{bmatrix} 0 & \omega & k_1 & 0 \\ -\omega & 0 & 0 & k_1 \\ -k_2 & 0 & 0 & 0 \\ 0 & -k_2 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ k_2 & 0 \\ 0 & k_2 \end{bmatrix}$$

dq = $-v_{Ld}^{*}$ + (1/k_2)ωi_{Lq}, and dq = $-v_{Lq}^{*}$ + (1/k_2)ωi_{Ld}.

Note that u_d is applied to compensate for the system uncertainties as a compensating term. Consider the following Riccati equation for the solution matrix P:

$$PA + A^T P - PBR^{-1}B^T P + Q = 0 \tag{5}$$

where Q and R are the positive definite weighting matrices with sufficient dimensions.

Remark 1**:** Recall that Q and R are the weighting matrices. Excessive large error or control input values can be penalized by using properly chosen Q and R. Generally, the large Q means a high control performance, whereas the large R means a small input magnitude.

Let the diagonal matrices Q and R be defined as

$$Q = \begin{bmatrix} Q_1 & 0 & 0 & \dots & 0 \\ 0 & Q_2 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & \dots & 0 & Q_m \end{bmatrix}$$

$$R = \begin{bmatrix} R_1 & 0 & 0 & \dots & 0 \\ 0 & R_2 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & \dots & 0 & R_k \end{bmatrix}$$

where Q and R have positive diagonal entries such that √Qi = $1/y_i^{max}$, where i = 1, 2, . . . , m, and √Ri = $1/u_i^{max}$, where i = 1, 2, . . . , m. The number yimax is the maximally acceptable deviation value for the ith component of output y. The other quantity u_i^{max} is the i^{th} component of input u. With an initial guessed value, the diagonal entries of Q and R can be adjusted through a trial-and-error method. Then, the optimal voltage controller can be designed by the following equation:

$$u = -u_d + kx \tag{6}$$

where K = $-R^{-1}$ B^T P denotes the gain matrix, and u_d and K_x represent a feed forward control term and a feedback control term, respectively.

Remark 2: The proposed voltage controller, in essence, is designed based on the well-known linear quadratic regulator minimizing the following performance index.

$$J = \int_0^{\infty} (x^T Q_x + u_n^T R u_n) dt \tag{7}$$

where x is the error, $u_n = u + u_d$, and Q and R are symmetrical positive definite matrices as mentioned above.

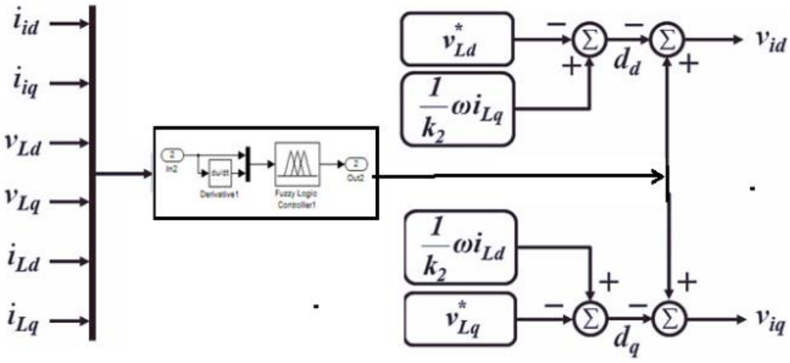

Fig. 2. Block diagram of the proposed optimal voltage control scheme.

B. Stability Analysis of Voltage Controller

Consider the following Lyapunov function:

$$V(x) = x^T P x \tag{8}$$

From (4)–(6), and (8), the time derivative of V(x) is given by the following:

$$V(\dot{x}) = \frac{d}{dt} x^T P x = 2x^T P(A + BK)x = 2x^T P(A - BR^{-1}B^T P)x = x^T(PA + A^T P - 2PBR^{-1}B^T P)x \leq -x^T Q_x \tag{9}$$

This implies that x exponentially converges to zero.

Remark 3: By considering the parameter variations, the state-dependent coefficient matrix A is rewritten as A'= A + ΔA, where ΔA means the value of system parameter variations. Thus, (4) can be transformed into the following error dynamics:

$$\dot{x} = A'x + B(u + u_d) \tag{10}$$

The new time derivative of (8) is given by the following:

$$\dot{V}(x) = \dot{2}x^T P\dot{x} = x^T(PA + P\Delta A + \Delta A^T P + A^T P - 2PBR^{-1}B^T P)x < 0 \quad (11)$$

By (5), (11) is reduced to

$$\dot{V}(x) = x^T(P\Delta A + \Delta A^T P - Q - PBR^T B^T P)x \quad (12)$$

If the following inequality holds for the given ΔA:

$$P\Delta A + \Delta A^T P < PBR^{-1}B^T P + Q \quad (13)$$

then V < 0 for all nonzero x. Therefore, the proposed
optimal voltage control system can tolerate any parameter variation satisfying (13).

IV. OPTIMAL LOAD CURRENT OBSERVER DESIGN AND STABILITY ANALYSIS

A. Optimal Load Current Observer Design

To avoid using current sensors, a linear optimal load current observer is introduced in this algorithm. As seen in (2) and (4), the inverter current references (i^*_d and i^*_q) and feed forward control term (u_d) need load current information as inputs. From (1) and the assumption, the following dynamic model is obtained to estimate the load current:

$$\begin{cases} x_0 = A_0\dot{x}_0 + B_0u_0 \\ y = C_0x_0 \end{cases} \quad (14)$$

where xo = [i_{Ld} i_{Lq} v_{Ld} v_{Lq}] ^{T}, uo = [k_1 i_{id} k_1 i_{iq}] ^{T},

$$A_0 = \begin{bmatrix} 0 & \omega & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -k_1 & 0 & 0 & \omega \\ 0 & -k_1 & -\omega & 0 \end{bmatrix}, \; B_0 = C_0^T = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Then, the load current observer is expressed as

$$\dot{\hat{x}}_0 = A_0\hat{x}_0 + B_0u_0 - L(y - C_0\hat{x}_0) \quad (15)$$

where x_0 = [i_{Ld} i_{Lq} v_{Ld} v_{Lq}]^T, and i_{Ld} and x_{Lq} are estimates of i_{Ld} and i_{Lq}, respectively. In addition, L is an observer gain matrix calculated by

$$L = -P_0C_0^T R_0^{-1} \quad (16)$$

and P_o is the solution of the following Riccati equation:

$$A_0P_0 + P_0A_0^T - P_0C_0^TR_0^{-1}C_0P_0 + Q_0 = 0 \tag{17}$$

Remark 4: The fourth-order Kalman–Bucy optimal observer is used to minimize the performance index $E(x^T_e\ x_e)$, where x_e=x_o–x_o, representing the expectation value of $x^T_e\ x_e$ for the following perturbed model:

$$\dot{x_0} = A_0x_0 + B_0u_0 + d,\ y = C_0x_0 + v \tag{18}$$

where d ∈ R^4 and v ∈ R^2 are independent white Gaussian noise signals with E(d) = 0, E(v) = 0, $E(dd^T) = Q_o$, and $E(vv^T) = R_o$.

B. Stability Analysis of Load Current Observer

The error dynamics of the load current observer can be obtained as follows:

$$\dot{x}_e = (A - LC)x_e \tag{19}$$

Define the Lyapunov function as

$$V_0(x_e) = x_e^TXx_e \tag{20}$$

where X = P_0^{-1} . Its time derivative along the error dynamics (19) is represented by the following:

$$\dot{V}_0(\tilde{x}) = \frac{d}{dt}x_e^TXx_e = 2x_e^T(XA_0 - XP_0C_0^TR_0^{-1}C_0)x_e = x_e^TX(A_0P_0 + P_0A_0^T - 2P_0C_0^TR_0^{-1}C_0P_0)Xx_e \leq -x_e^TXQ_0Xx_e \tag{21}$$

This implies that x_e exponentially converges to zero.

V. OBSERVER-BASED CONTROL LAW AND CLOSED-LOOP STABILITY ANALYSIS

A. Observer-Based Control Law

With the estimated load currents achieved from the observer instead of the measured quantities, the inverter current errors and feed forward control term can be obtained as follows:

$$\bar{\imath}_{de} = i_{id} - \hat{\imath}_{Ld} + \frac{1}{k_1}\omega v_{Lq}^*, \quad \bar{\imath}_{qe} = i_{iq} - \hat{\imath}_{Lq} - \frac{1}{k_1}\omega v_{Ld}^*$$

$$\bar{d}_d = -v_{Ld}^* + \frac{1}{k_2}\omega\hat{\imath}_{Lq},\ \bar{d}_q = -v_{Lq}^* - \frac{1}{k_2}\omega\hat{\imath}_{Ld} \tag{22}$$

Then, (22) can be rewritten as the following equations:

$$\bar{\imath}_{qe} = i_{de} + [1 \quad 0 \quad 0 \quad 0]x_e$$

$$\bar{\iota}_{qe} = i_{qe} + [0 \quad 1 \quad 0 \quad 0]x_e$$

$$\bar{d}_d = d_d + \frac{\omega}{k_2}[0 \quad 1 \quad 0 \quad 0]x_e$$

$$\bar{d}_q = d_q - \frac{\omega}{k_2}[1 \quad 0 \quad 0 \quad 0]x_e \tag{23}$$

From (6) and (23), the proposed observer-based control law can be achieved as

$$u = -\bar{u}_d + K\bar{x} \tag{24}$$

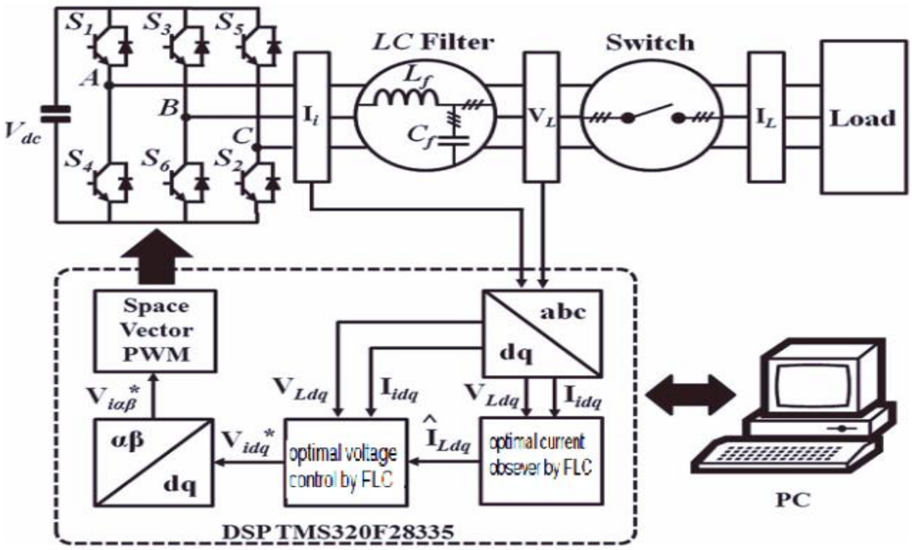

Fig. 3. Block diagram of the proposed observer-based optimal voltage control system with FLC.

B. Closed-Loop Stability Analysis

For the purpose of analyzing the stability, (24) is rewritten as the following:

$$u = -u_d + Kx + Hx_e \tag{25}$$

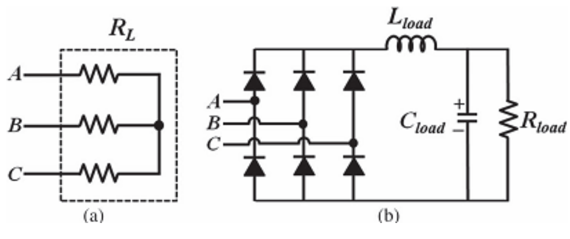

Fig.4. Two types of load circuits. (a) Resistive linear load. (b) Nonlinear load with a three-phase diode rectifier.

Table I: System Parameters of A 600-VA Testbed

Parameters	Descriptions	Values	Units
V_{dc}	dc-link voltage	290	[V]
T_s	Sampling time	200	[µs]
f_s	Switching frequency	5	[kH]
f_1	Fundamental frequency	60	[Hz]
$V_{L,\ rms}$	Load output voltage	110	[V]
L_f	Output filter inductance	10	[mH]
C_f	Output filter capacitance	7	[µF]
R_L	Resistance for linear load	60	[Ω]
R_{load}	Resistance for nonlinear load	200	[Ω]
C_{load}	Capacitance for nonlinear load	650	[µF]
L_{load}	Inductance for nonlinear load	4	[mH]

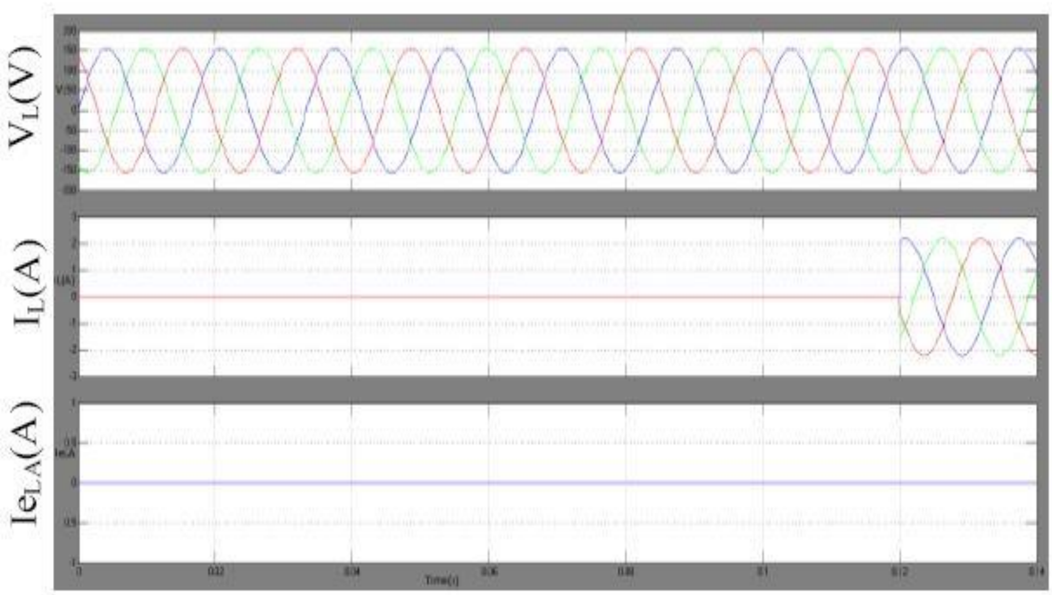

Fig.5. Simulation result of the proposed observer based optimal voltage control scheme by using fuzzy under load step change with −30% parameter variations in L_f and C_f (i.e., balanced resistive load: 0%–100%)6-First: Load output voltages (V_L), Second: Load output currents (I_L), Third: Phase A load current error.

IV. PERFORMANCE VALIDATIONS

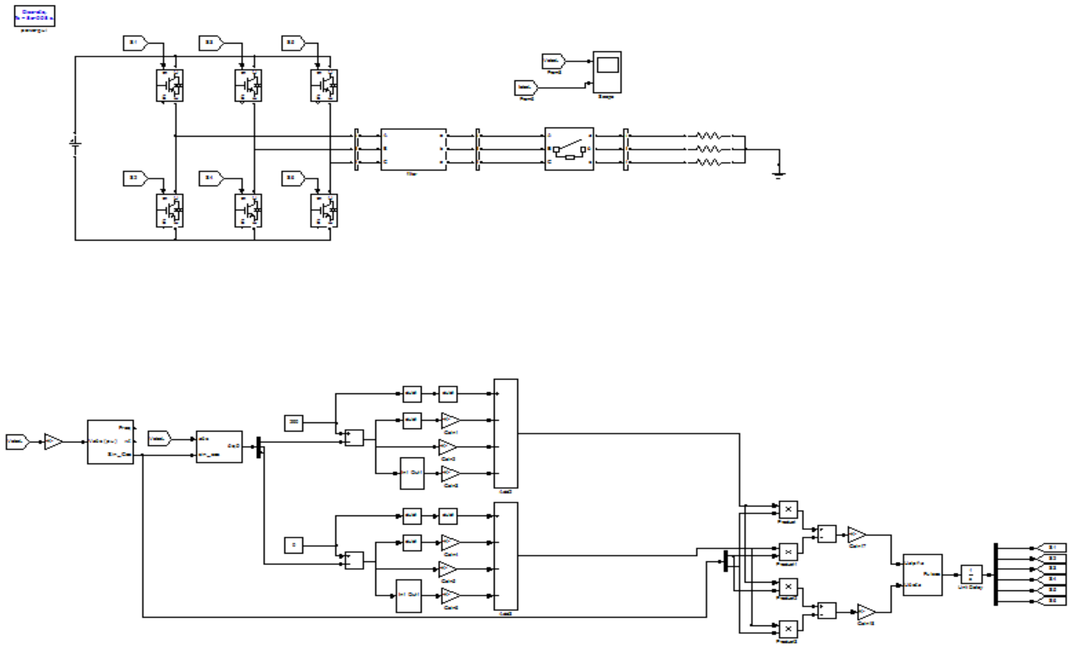

Fig.6. Simulation model

A. Test bed Description:

The proposed observer-based optimal voltage controller has been performed through both simulations with MATLAB/ Simulink and experiments with a prototype 600VA UPS inverter test bed. Moreover, the conventional FLC scheme is adopted to exhibit a comparative analysis of the proposed.

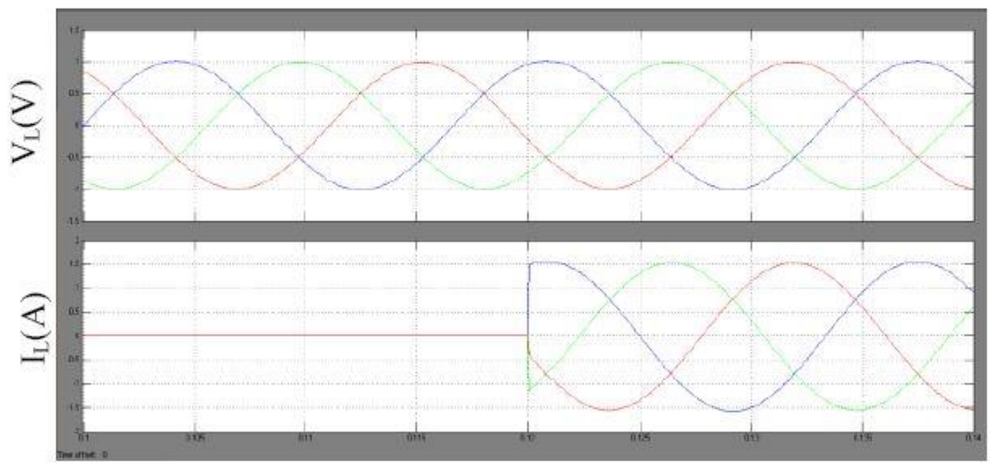

Fig.7. Simulation results of the conventional FLC scheme by using fuzzy under load step change with −30% parameter variations in L_f and C_f (i.e., balanced resistive load: 0%–100%)—First: Load output voltages (V_L), Second: Load output currents (I_L).

Control scheme since it reveals a reasonable performance for nonlinear load and has the circuit model of a three-phase inverter similar to our system. Fig. 3 illustrates the overall block diagram to carry out the proposed algorithm using a 16-bit floating-point TMS320LF28335 DSP. In the test bed, the inverter phase currents and line-to-neutral load voltages are measured via the CTs and PTs to implement the feedback control. In this paper, a space vector PWM technique is used to generate the control inputs ($V_{i\alpha}$ and $V_{i\beta}$) in real time.

Table II. Steady-S Tate Performances of the Proposed and Conventional Schemes by Using Fuzzy

Control Scheme			The Proposed Observer Based Optimal Voltage Control Scheme		
Load Condition			Step Change	Unbalanced	Nonlinear
THD(%)	Simulation		0.10	0.11	0.47
Load RMS Voltage(V)	Simulation	V_{LA}	109.9	109.9	109.6
		V_{LB}	109.8	110.0	109.95
		V_{LC}	110.1	109.9	109.7
Control Scheme			The Conventional FLC Scheme		
Load Condition			Step Change	Unbalanced	Nonlinear
THD(%)	Simulation		0.11	0.47	0.47
Load RMS Voltage(V)	Simulation	V_{LA}	109.7	110.3	110.3
		V_{LB}	110.0	110.6	110.3
		V_{LC}	109.8	110.6	110.3

B. Simulation Results:

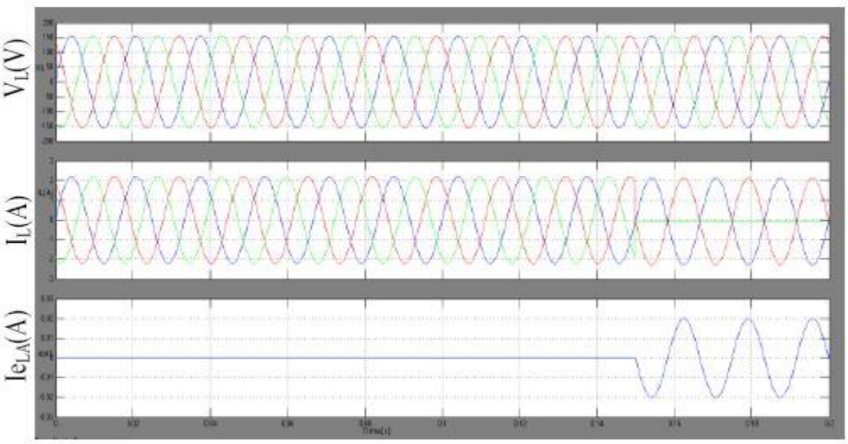

Fig.8. Simulation results of the proposed observer based optimal voltage control scheme by using fuzzy under unbalanced load with −30% parameter variations in L_f and C_f (i.e., phase B opened)—First: Load output voltages (V_L), Second: Load output currents (I_L), Third: Phase A load current error ($i_{eLA} = i_{LA} - \hat{i}_{LA}$).

The proposed voltage control algorithm is carried out in various conditions (i.e., load step change, unbalanced load, and nonlinear load) to impeccably expose its merits. In order to instantly engage and disengage the load during a transient condition, the on–off switch is employed as shown in Fig. 3.

The resistive load depicted in Fig. 4(a) is applied under both the load step change condition (i.e., 0%–100%) and the unbalanced load condition (i.e., phase B opened) to test the robustness of the proposed scheme when the load is suddenly disconnected. In practical applications, the most common tolerance variations of the filter inductance (L_f) and filter capacitance (C_f), which are used as an output filter, are within ±10%. To further justify the robustness under parameter variations, a 30% reduction in both L_f and C_f is assumed under all load conditions such as load step change, unbalanced load, and nonlinear load.

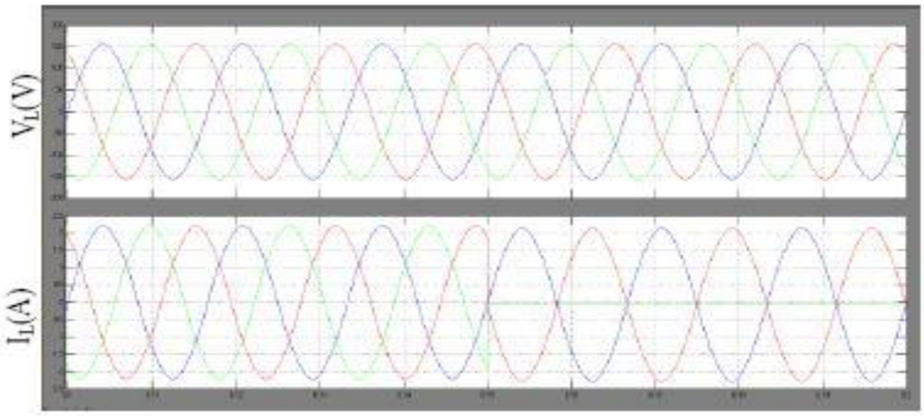

Fig.9. Simulation results of the conventional FLC scheme by using fuzzy under unbalanced load with −30% parameter variations in L_f and C_f (i.e., phase B opened) —First: Load output voltages (V_L), Second: Load output currents (I_L).

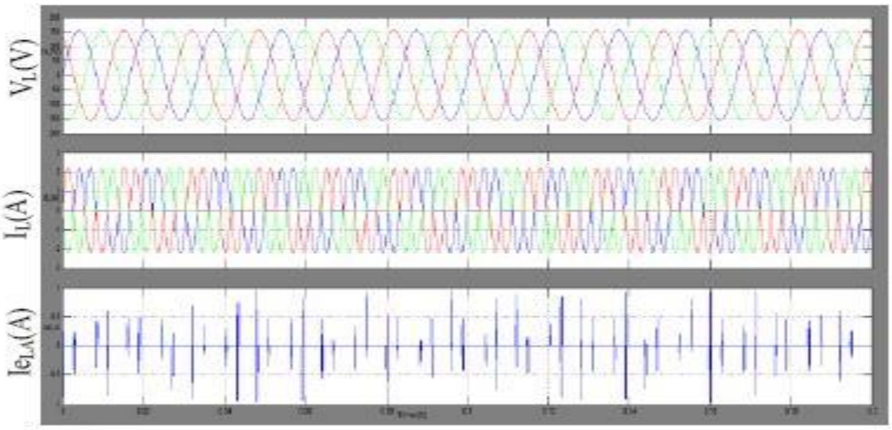

Fig.10. Simulation and experimental results of the proposed observer based optimal voltage control scheme by using fuzzy under nonlinear load with −30% parameter variations in L_f and C_f (i.e., three-phase diode rectifier)—First: Load output voltages (V_L), Second: Load output currents (I_L), Third: Phase A load current error ($i_{eLA} = i_{LA} - \hat{i}_{LA}$).

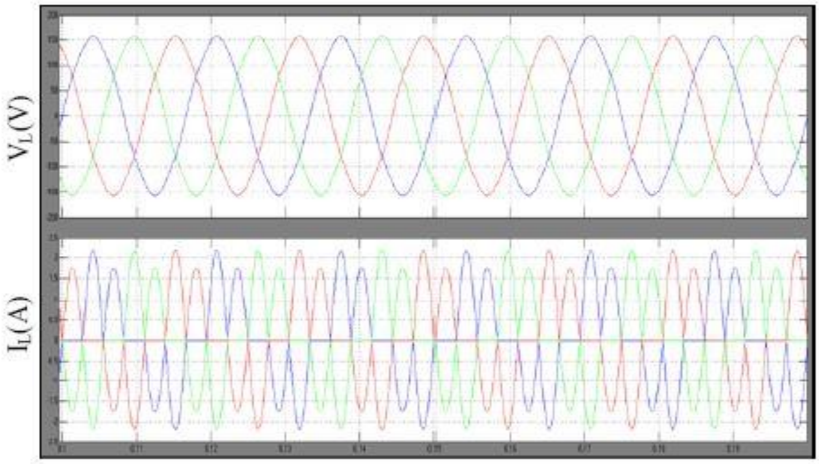

Fig.11. Simulation results of the conventional FLC scheme by using fuzzy under nonlinear load with −30% parameter variations in Lf and C f (i.e., three-phase diode rectifier)—First: Load output voltages (VL), Second: Load output currents (IL).

VI. FUZZY LOGIC CONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC. The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's, 'min' operator. v. Defuzzification using the height method.

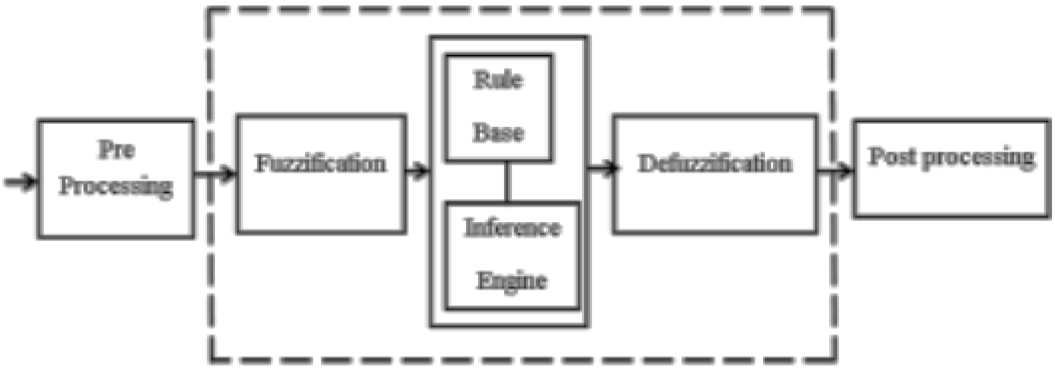

Fig.12. Fuzzy logic controller

***Fuzzification*:** Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB, NM, NS, ZE, PS, PM, and PB. The partition of fuzzy subsets and the shape of membership CE(k) E(k) function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor.

Table 1: Fuzzy Rules

Change In Error	Error						
	NB	**N M**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular E(k) input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \tag{26}$$

$$CE(k) = E(k) - E(k-1) \tag{27}$$

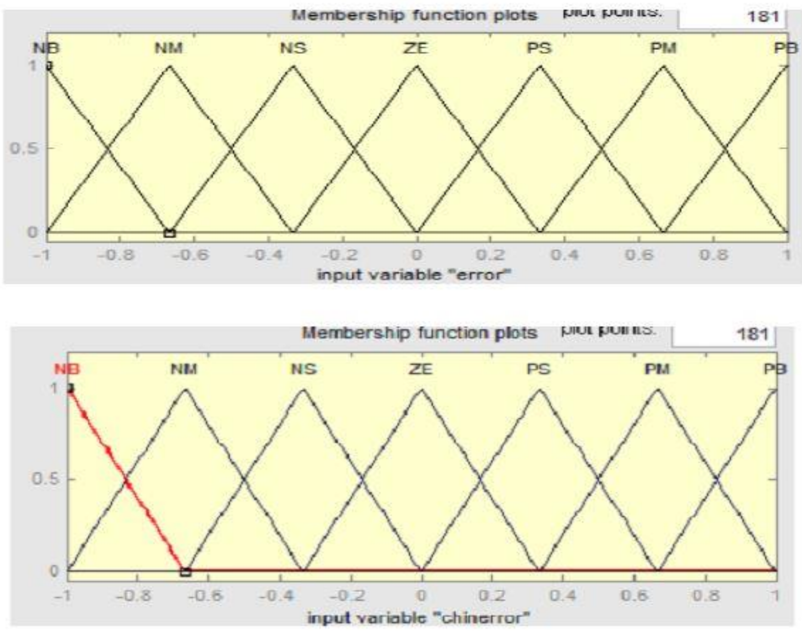

Fig.13. Membership functions

***Inference Method*:** Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

Defuzzification: As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, height method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output.
The set of FC rules are derived from

$$u=-[\alpha E + (1-\alpha)*C] \tag{28}$$

CONCLUSION

In this paper a simple observer-based optimal voltage control method of the three-phase UPS systems is proposed the proposed controlling is based on fuzzy logic controller. Moreover, the optimal load current observer was used to optimize system cost and reliability. This paper proved the closed-loop stability of an observer-based optimal voltage controller by using the Lyapunov theory. Optimal voltage control scheme for three-phase UPS systems has a good voltage regulation capability such as fast transient behavior, small steady-state error. This has low THD under various load conditions such as load step change, unbalanced load, and nonlinear load in the existence of the parameter variations. The optimal control has good properties such as enough gain and phase margin, robustness to uncertainties, good tolerance of nonlinearities. The performance of the proposed system is shown in simulation results. Here fuzzy logic controller is used compared to other controllers. To gain better optimal voltage control.

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