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A Study on the Voltage Control Scheme for Three-Phase UPS Systems

J.Rakesh Sharan, M.Tech
Associate Professor
Department of EEE
Sri Indu College of Engineering
And Technology (Autonomous)
Hyderabad,Telangana.

A.Mamatha
M.Tech Student
Department of EEE
Sri Indu College of Engineering
And Technology (Autonomous)
Hyderabad,Telangana.

Prof. M.Shiva Kumar
HoD & Professor
Department of EEE
Sri Indu College of Engineering
And Technology (Autonomous)
Hyderabad,Telangana.

Abstract

An uninterruptible power supply, also uninterruptible power source, UPS or battery/flywheel backup is an electrical apparatus that provides emergency power to a load when the input power source or mains power fails. A UPS differs from an auxiliary or emergency power system or standby generator in that it will provide near-instantaneous protection from input power interruptions, by supplying energy stored in batteries, supercapacitors, or flywheels. The on-battery runtime of most uninterruptible power sources is relatively short (only a few minutes) but sufficient to start a standby power source or properly shut down the protected equipment.

A UPS is typically used to protect hardware such as computers, data centers, telecommunication equipment or other electrical equipment where an unexpected power disruption could cause injuries, fatalities, serious business disruption or data loss. UPS units range in size from units designed to protect a single computer without a video monitor (around 200 volt-ampere rating) to large units powering entire data centers or buildings. The world's largest UPS, the 46-megawatt Battery Electric Storage System (BESS), in Fairbanks, Alaska, powers the entire city and nearby rural communities during outages.[1]

A voltage controller also called an AC voltage controller or AC regulator is an electronic module based on either thyristors, TRIACs, SCRs or IGBTs, which converts a fixed voltage, fixed frequency alternating current (AC) electrical input supply to obtain variable voltage in output delivered to a resistive load. This varied voltage output is used for dimming street lights, varying heating temperatures in homes or industry, speed control of fans and winding machines and many other applications, in a similar fashion to an autotransformer.[1][2] Voltage controller modules come under the purview of power electronics. Because they are low-maintenance and very efficient, voltage controllers have largely replaced such modules as magnetic amplifiers and saturable reactors in industrial use.[2]

Key Words: *Optimal load current observer, optimal voltage control, three-phase inverter, total harmonic distortion (THD), uninterruptible power supply (UPS).*

INTRODUCTION

Uninterruptible power supply (UPS) systems supply emergency power in case of utility power failures. 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.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. To improve the aforementioned performance indexes, a

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number of control algorithms have been proposed such as proportional–integral (PI) control, H∞ loop-shaping control, model predictive control, deadbeat control, sliding-mode control, repetitive control, adaptive control, and feedback linearization control (FLC).

The conventional PI control suggested is easy to implement; however, the THD value of the output voltage is not low under a nonlinear-load condition. 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. In model predictive control method for UPS applications a load current observer in place of current sensors, the authors claimed a reduced system cost. However, the simulation and experimental results do not reveal an exceptional performance in terms of THD and steady-state error. The deadbeat control method uses the state feedback information to compensate for the voltage drop across the inductor. However, this method exhibits sensitivity to parameter mismatches, and the harmonics of the inverter output voltage are not very well compensated. The sliding-mode control technique reflects robustness to the system noise, and still, the control system has a well-known chattering problem. Repetitive control is applied to achieve a high-quality sinusoidal output voltage of a three-phase UPS system. Generally, this control technique has a slow response time. The adaptive control method with low THD is proposed; nevertheless, there is still a risk of divergence if the controller gains are not properly selected. Multivariable FLC is presented. In this control technique, the nonlinearity of the system is considered to achieve low THD under nonlinear load. However, it is not easy to carry out due to the computation complexities. As a result, the aforementioned linear controllers are simple, but the performance is not satisfactory under nonlinear load. In contrast, the nonlinear controllers have an outstanding performance, but the implementation is not easy due to the relatively complicated controllers.

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 magnitudes and tracking error unlike previous algorithms. The efficacy of the proposed control method is verified via simulations on MATLAB/Simulink and experiments on a prototype 600-VA UPS inverter testbed with a TMS320LF28335 DSP. In this paper, a conventional FLC method is selected to demonstrate the comparative results because it has a good performance under a nonlinear-load condition, and its circuit model of a three-phase inverter is similar to our system model. Finally, the results clearly show that the proposed scheme has a good voltage regulation capability such as fast transient behavior, small steady-state error, and low THD under various load conditions such as load step change, unbalanced load, and nonlinear load in the existence of the parameter variations.

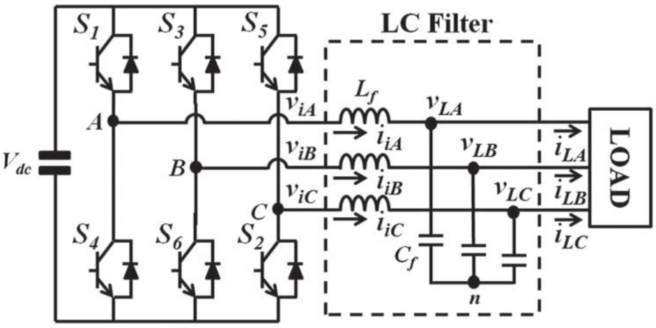

Fig. 1.1: Three phase inverter with an LC filter for a UPS system

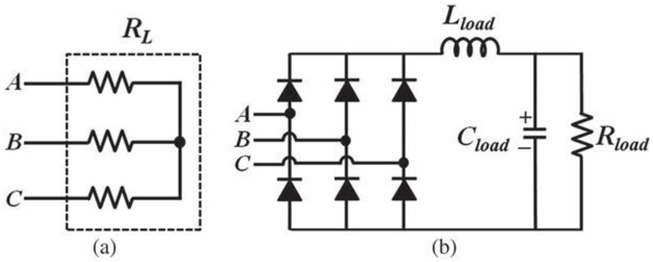

Fig. 1.2: Two types of load circuits. (a) Resistive linear load. (b) Nonlinear load with a three-phase diode rectifier.

CONTROLING METHODS

Proposed Method:

Different techniques and circuits have been so far recommended to improve UPS performance and obtain ideal specifications. The design consideration and digital control technique of an on-line, lowcost, high performance and single-phase UPS system based on a boost integrated fly-back rectifier/energy storage dc/dc converter is proposed. This controller follows the reference current and voltage of the inverter with a delay of two and four sampling periods, respectively. A feedback linearization approach base on pole placement technique to control the output voltage control of threephase UPS systems is proposed. A control scheme using predictive control for a two-level converter is presented, which a cost function is used for selecting the switching state and an observer is used for load current estimation. A feedback linearization technique base on linear control theory to control of the output voltage of three-phase UPS systems is proposed, which the tracking control law is obtained with a pole placement technique.

Classification of Control Techniques:

Based on the control system objectives, feedback control schemes for UPS inverters may be classified as follows.

Continues-Time and Discrete-Time Control :

Feedback control strategies devised for UPS inverters can be broadly classified as continuous-time control (CTC) and discrete-time control (DTC).

With advent of fast microcontrollers, DTC strategies have been proposed. The response time of such schemes are limited by microcontroller speed and give rise to considerable distortion with nonlinear loads. CTC strategies are much faster and can lead to much less distortion. An optimal control method based on the linear quadratic regulator (LQR) approach is proposed in continuous-time for single phase UPS inverter. Discrete-time LQR technique with repetitive controller is proposed, which the LQR parameters are calculated by minimizing a cost function.

Repetitive Control:

Repetitive control (RC) can be regarded as a simple learning control because the control input is calculated using the information of the error signal in the preceding periods. Repetitive controller is a learning controller that uses the information of the output error in the previous cycles to compute the repetitive action. RC is one of attractive methods in the practical applications due to the simplicity of its algorithm and of independence varying samples from the output voltage. If the repetitive control is directly combined with PWM inverter, it can generate a good quality voltage with minimum cost. When the reference signal has harmonic components in the order of the fundamental frequency, the RC improves the steady state response of the system. This method is easily applied and only requires the measured output voltage but the dynamic response of the system is slow. Designing a repetitive controller for open loop SPWM is not easy due to the inverter dynamic particularly in the no-load mode. Repetitive controller needs a complicated compensating network capable to sample the load periodically. The major objective of the RC is the use of repetitive nature in disturbances and faults and compensating the output voltage at any cycle. This method is not suitable during non-periodic transient modes such as switching. If a good dynamic during switching is required, an instantaneous feedback control is used.

A conventional feedback controller is utilized to increase the stability margin of the closed loop systems. A repetitive controller consists of three tracking controller (G1), continual controller (G2) and parameter tuning controller (G3). When the controller is used to eliminate the oscillating or periodical disturbances, controller is employed for improvement of the transient mode response. The adaptive algorithm estimates the parameter G3 of the system parameters and the continual controller is regulated for stability assurance and automatic quick elimination of the periodical disturbances over all frequency modes. So far, many strategies have been employed for RC in industry. The RC has been combined with pole

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placement technique. In this method, parameter changes because a small change in the pole places. Designing pole transfer controller is easy, because it does not need a quick response and minimal steady state error simultaneously. A reference model controller with RC for UPS has been recommended based on the least square error method which is stable for a wide range of the filter parameters. A repetitive learning controller is used to obtain high quality output waveform from an inverter feeding a non linear load. An adaptive repetitive control scheme that employs an auxiliary compensator to stabilize the closed loop system even with variations in the plant is presented. A robust model reference adaptive controller is presented including a repetitive control for UPS applications. It can effectively eliminate periodic waveform distortion resulted by unknown periodic disturbances, and is globally stable in the presence of un-modeled dynamics.

Iterative Learning Controller:

The iterative learning controller (ILC) provides a solution for minimization of periodic errors due to nonlinear loads, especially for low frequency harmonic components. ILC is implemented through memory based learning approach. The ILC as shown in Block diagram of iterative learning controller is comprised of feed forward learning loop from previous learning cycle error and feedback learning loop from instant error.

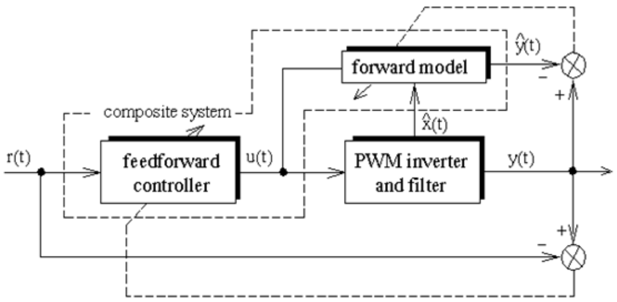

Fig. 2.1: Block diagram of iterative learning controller

This control scheme learns a feed forward signal as a function of the time. A drawback of the ILC scheme is that it can only be applied if the task is repetitive. The ILC problem setting is very similar to the RC case, but the only difference is that whereas in ILC the state of the system is reset to initial condition at the end of the period, in RC the initial condition for each period is the final state from previous period. A current regulation method based on iterative control technique is proposed in order to reduce the distortions caused by both the dead-time and the zero crossing problems. A ILC scheme in discrete time domain for an inverter system used in ac power sources minimizes periodic errors caused by both linear load and non linear load.

Instantaneous Feedback Control:

The instantaneous feedback control (IFC) techniques have been applied to improve the dynamic transient response, obtain output voltage with low THD and improved disturbance rejection via lower output impedance. This approach has the disadvantage that harmonics are generated in the output voltage at frequencies around the switching frequency. Many fast response IFC strategies such as deadbeat control and cascade control have been developed for distinct applications to achieve ero steady state error and fast transient response which can occur under nonlinear loads.

Deadbeat Controller:

Digital system controller is used in the design of inverter systems in order to obtain a suitable response against sudden change of the loads. In a digital control system, the signal over one or many points is expressed as a numerical code in a digital converter. Instantaneous feedback control techniques using dead beat control are for improving the transient response and compensating the PWM inverter waveform. DTC strategies are mostly based on the deadbeat control (DBC) theory. DBC was introduced in the middle of decade 1980. In DBC technique, a CTC system is converted into a discrete system and a DBC from output variable over minimum sampling time is obtained by applying a suitable feedback. This method is the best way for obtaining a quick response in the control of inverter voltage, but it is very sensitive in applying to a UPS system. DBC, which originated from states equations, has very fast dynamic response and can eliminate voltage variation in several control periods. Also for a full digitalizing, UPS systems with low capacity are used. In this method, the design objective is to minimize the maximum jumping and making quickly the rise time of the response. Contrary to analogue control systems, the response for digital control systems is unique and system is only adjusted for the designed input, and it does not show a good performance againstother inputs and has high sensitivity to the load change. The technique of locating all poles of a discrete time system at zero equals DBC method. A digital signal processor in a UPS system with inverter has been given for providing a sinusoidal waveform; the control design consists of regulator for load rms current and voltage, in order to make ineffective the output voltage harmonics in a stable system. To achieve a desirable dynamic response and output voltage independent of the load change or parameters, digital multiple feedback control (DMFC) technique has been used for control of PWM inverter; this increases the cost of software and hardware parts. A DMFC has been suggested for a single phase half bridge in a UPS system in which control is based on the measurement of the capacitor filter voltage and load current, and the observed mode is used for prediction of the capacitor current. The current digital control system has been presented based on two observers and one compensator and stability of the system has been studied against parameters variations. A deadbeat controller with repetitive integral action suitable for UPS to achieve a deadbeat dynamic response for the controlled variables is presented.

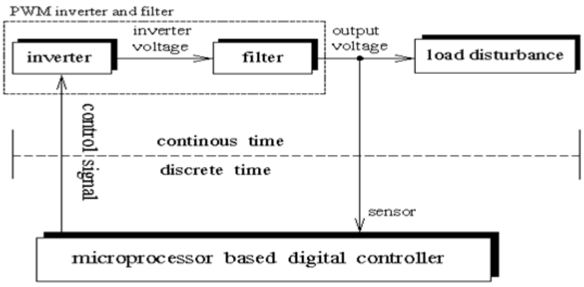

Fig. 2.2: Block diagram for deadbeat control of PWM inverter

State Feedback Controller:

To obtain a satisfying dynamic behavior of the closed loop system a state feedback applied. A powerful analytical method in state variables domain is used in the design of state feedback. The design of a stable feedback control system is based on a suitable selection of the feedback system structure. When all state variables are not achievable, the design output feedback. The typical architecture of applies feedback control system consists of a plant whose performance is controlled by an actuator. The actuator receives command signals from the controller, which calculates it in accordance with the respective reference input and feedback signals from the sensor. A combination of state feedback control and repetitive control is proposed. This hybrid achieves excellent dynamics and low THD with nonlinear loads, but the magnitude of the output voltage is subject to variations with load changes. A design procedure of a predictive digital state feedback control to ensure a sufficient quality of the output voltage under typical linear and nonlinear load conditions for a single phase ups inverter is shown. A robust state feedback control based on a linear matrix inequality design has been applied to a UPS system. A repetitive control is combined with least square error (LSE) state feedback control, in the IFC scheme, serving as the inner loops.

Nonlinear Control:

Nonlinear controllers generally present good dynamical response, robustness and stability. In nonlinear control, the concept of feedback plays a fundamental role in controller design, as it does in linear control. However, the importance of feed forward is much more conspicuous than in linear control. Very often it is impossible to control a nonlinear system stably without incorporating feed forward action in the control law. The use of nonlinear feedback makes the control system robust and less sensitive to load disturbances and output filter circuit parameter variations. Switching delays and loss limit the use of this control technique in low power single phase UPS inverter. A nonlinear feed forward controller using one cycle based PWM generator and an output feed forward current is applied to a single phase UPS.

An improved nonlinear control based on the pole placement technique of the inverter output voltage for the three-phase UPS systems is proposed, which it is shown that the proposed control scheme gives high dynamic responses at load variation as well as a zero steady-state error.

Sliding Mode Control:

Sliding mode control (SMC), also called variable structure control (VSC), as a non−linear control technique was introduced in 1950. Basically, a SMC system is a switching control rule for guiding system to the designed modes with the relevant curve of the system. When a good transient response is required from output voltage, the equation of the sliding level in the space state is written by a linear combination of error of state variable.

This error has been defined differently in various papers. In the SMC method, apart from the starting points in the state space, the system paths must be confronted with the sliding level and the movement of system on the sliding level must reach a stable point corresponding to the required voltage and current. The method provides a systematic balance for preserving the stability. This method is not sensitive to the variation of the parameters of the system and external disturbances. The main problem with this method is the system indifference to the unknown parameters and external disturbances. The major obstacle for the application of the SMC in inverter is the diversity of the switching frequency for the switch that produces a large amount of noises with high frequency and THD.

Feed controllers gain which is generally constant, varies in respect to the state variables in the SMC. Fig. 7 shows the discrete feed forward SMC scheme, where the control force (U) is composed of two parts: a feed forward control force (UF) and an SMC force (US).

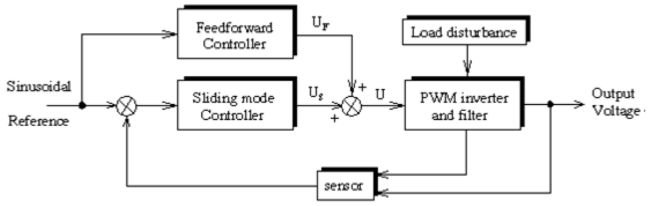

Fig. 2.4: Discrete feed forward sliding mode control scheme

The SMD design steps could be summarized as: (1) proposing the sliding surface, (2) verifying the existence of a sliding mode and (3) analyzing the stability in sliding surface. Many papers have been published in the field of sliding mode control. A two level PWM inverter with fixed switching frequency and current limiter is proposed, the overall performance is good, but two current measurements are required for the load and filter inductor currents, so it is not attractive from the cost and control points of view. An SMC is proposed where a periodic disturbance signal is added to make a pulse to pulse limit of the sliding surface function into low bound. It has the advantages of fixed switching frequency, current limiting and no additional load current measurement, but the load current observer will increase the circuit complexity. A discrete time SMC algorithm for UPS inverter has been presented based on a two loop design in which the effect of load current and inductance of filter for common control of PWM inverter has been used.

Space vector PWM technique:

Space vector PWM technique is an advancement of sinusoidal PWM as the pulses produced by digital switching of the fundamental waveform. Considering six switch operation we divide the VSI into two parts as upper part and lower part. The upper part contain the switches S1 S3 & S5 leaving the lower part of the VSI with S2 S4 & S6.

In the above mentioned 8 switching modes the first and the last are completely OFF and ON which is not applicable. We only consider the six states from 1st to 6th eliminating 0 and 7th mode. The last three switching states are the compliment of first three switching states, which concludes that we have to only generate the three switching states ie., 1st 2nd and 3rd. The other switching states ie., 4th 5th and 6th are generated by applying a NOT gate to the previous modes. A simple hexagonal representation of switching patter in shown below which can be called as Space vector Trajectory.

The signal generation of space vector is compared to the triangular waveform to generate three PWM pulses to which NOT gates are given to get the other three pulses. The control signal of space vector PWM is given blow.

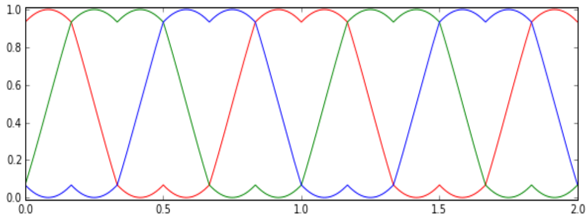

Fig. 3.12: Control signals of Space vector PWM

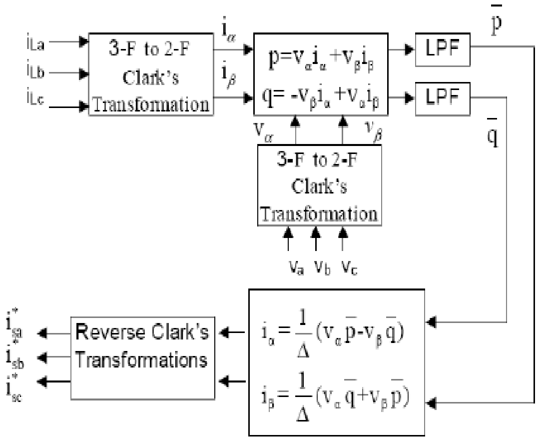

Fig. 3.16: Block diagram of IRP theory

In hysteresis control the reference signal isa* isb* & isc* are compared to measured values isa isb & isc, depending upon the error value logic '0' (LOW) or '1' (HIGH) is generated which was explained earlier in the paper.

The calculation comprises of Clarks transformation and Inverse Clarks transformation where the values are achieved by

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

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

The three phase instantaneous active power of the three phase system with a,b and c phase is given as

$$P_{3\phi} = v_a i_a + v_b i_b + v_c i_c$$

By using the transformation the active power can be calculated as

$$P_{3\phi}(t) = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0$$

With these values of α and β the values of p and q can be calculated

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{pmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{pmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

The calculated p and q components are fed to second order filters to reduce the disturbance caused during the change in the system. The filtered outputs are now used to calculated the α and β components of the currents. The two components of the currents are converted to a, b and c reference current values by using Inverse Clarks transformation.

$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} -i_o \\ i^*_{f\alpha} \\ i^*_{f\beta} \end{bmatrix}$$

The values of the reference signals are used to generate pulses with the use of PWM (Pulse Width Modulation) and generate the required modulation index pulses with synchronization to the grid.

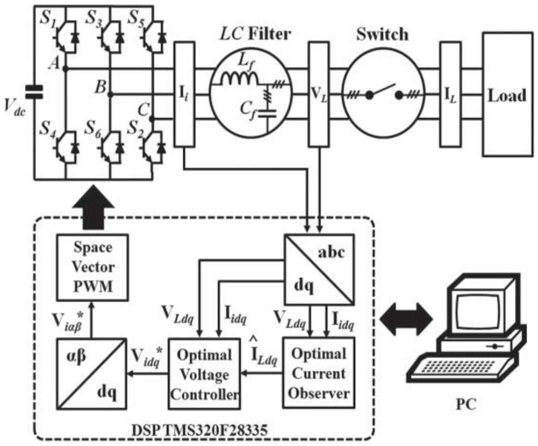

Fig. 3.17: Block diagram of the proposed observer based optimal voltage control system

This implies that x and xe exponentially go to zero.

As a result, the design procedure of the proposed observer-based control law can be summarized as follows.

Step 1) Build system model (1) in the d − q coordinate frame and then derive error dynamics (4) by using system parameters.

Step 2) Set the optimal voltage controller (6) with the feed-forward control term (ud) and feedback control term (Kx).

Step 3) Define the load current estimation model (14) and build the load current observer (15) by using the Kalman–Bucy optimal observer.

Step 4) Select the observer weighting matrices Qo and Ro in Riccati equation by referring to Remark 1. Then, choose the observer gain L in (16) using Qo and Ro.

Testbed Description:

The proposed observer-based optimal voltage controller has been performed through both simulations with MATLAB/ Simulink and experiments with a prototype 600-VA UPS inverter testbed. Moreover, the conventional FLC scheme [17] is adopted to exhibit a comparative analysis of the proposedcontrol 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 testbed, 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 (Viα and Viβ) in real time. Table I lists all system parameters used in this study.

The proposed algorithm is verified through two different types of loads as explicitly depicted in Fig. 4. More specifically, Fig. 4(a) shows a linear-load circuit that consists of a resistor per phase, whereas Fig. 4(b) depicts a nonlinear-load circuit that is comprised of a three-phase full-bridge diode rectifier, an inductor (Lload), a capacitor (Cload), and a resistor (Rload).

Note that during simulation and the experiment, observer gain L and controller gain K are selected based on Remark 1 as

Simulation and Experimental Results

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 (Lf) and filter capacitance (Cf), which are used as an output filter, are within ±10%. To further justify the robustness under parameter variations, a 30% reduction in both Lf and Cf is assumed under all load conditions such as load step change, unbalanced load, and nonlinear load.

Fig. 5 shows the simulation and experimental results of the proposed control method during the load step change. Moreover, Fig. 6 presents the comparative results obtained by employing the conventional FLC scheme under the same condition. Specifically, the figures display the load voltages (First waveform: VL), load currents (Second waveform: IL), and phase A load current error (Third waveform: ieLA = iLA −ˆiLA). It is important to note that the load current error waveform in the results of the conventional FLC method is not included because the FLC scheme does not need load current information. It can be observed in Fig. 5 that when the load is suddenly changed, the load output voltage presents little distortion. However, it quickly returns to a steady-state condition in 1.0 ms, as shown in the simulation results in Fig. 5(a). Moreover, it has revealed a fast recovery time of 1.5 ms in a real experimental setup as shown in Fig. 5(b). Conversely, as illustrated in the simulation results in Fig. 6(a), voltage distortion is larger, and its recovery time of 1.4 ms is much longer as compared with that in Fig. 5(a). Moreover, Fig. 6(b) shows a longer recovery time of 2.0 ms than that observed in Fig. 5(b). On the other hand, the THD values of the load output voltage at steady-state full-load operation are presented in Table II. These values are found as 0.11% for simulation and 0.89% for experiment using the proposed scheme. However, the conventional FLC scheme shows 0.94% and 1.32% for the case of simulation and experiment, respectively. Therefore, it is explicitly demonstrated that the proposed algorithm attains lower THD. It can be observed from Table II that the load root mean square (RMS) voltage values in both schemes are appropriately regulated at steady state. Moreover, the third waveform in Fig. 5 shows a small load current error (ieLA) between the measured value (iLA) and the estimated value (ˆiLA).

Next,thecharacteristic performances of the transient and steady state under unbalanced load are verified through Figs. 7 and 8. Precisely, this case is implemented under a full-load condition by suddenly opening phase B. It is shown that the load output voltages are controlled well, although the rapid change in the load current of phase B is observed as it is opened. As shown in Fig. 7, the respective THD values of the output voltage are 0.13% for the simulation and 0.91% for the experiment obtained by using the proposed method. However, the THD values are 0.97% and 1.39%, respectively, for the simulation and experiment in case of the conventional FLC scheme, as depicted in Fig. 8. As given in Table II, small steady-state voltage errors under unbalanced load are observed because the load RMS voltage values of both methods are almost 110 V. In addition, the load current observer provides high-quality information to the proposed controller as portrayed in Fig. 7.

To evaluate the steady-state performance under nonlinear load, a three-phase diode rectifier shown in Fig. 4(b) is used. The simulation and experimental results of each control method under this condition are demonstrated in Figs. 9 and 10.Tothis end, the THD values of the load voltage waveforms achieved with the proposed scheme are 0.89% for simulation and 1.72% for experiment, respectively. In the case of the conventional FLC scheme, the corresponding load voltage THD values are1.96% for simulation and 2.98% for experiment, respectively. It can be also observed that the proposed control strategy provides a better load voltage regulation in steady state compared with the conventional FLC method. In Fig. 9, it can be evidently seen that the load current observer guarantees a good estimation performance because of a small load current error (ieLA). Finally,all THD and load RMS voltage values under the three load conditions previously described are summarized in Table II.

A static VAR compensator (SVC) can also be used for voltage stability. However, a STATCOM has better characteristics than a SVC. When the system voltage drops sufficiently to force the STATCOM output current to its ceiling, its maximum reactive output current will not be affected by the voltage magnitude. Therefore, it exhibits constant current characteristics when the voltage is low under the limit. In contrast the SVC's reactive output is proportional to the square of the voltage magnitude. This makes the provided reactive power decrease rapidly when voltage decreases, thus reducing its stability. In addition, the speed of response of a STATCOM is faster than that of an SVC and the harmonic emission is lower. On the other hand STATCOMs typically exhibit higher losses and may be more expensive than SVCs, so the (older) SVC technology is still widespread.

Parameters of Test System:

TABLE 1
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]

Experimental results of the system:

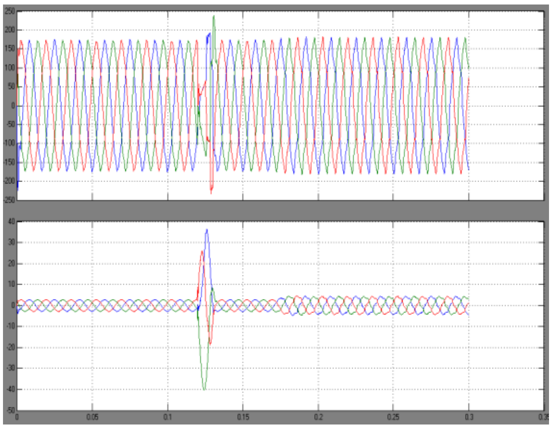

Fig. 4.3 Simulation and experimental results of the proposed observerbased optimal voltage control scheme under load step change with −30% parameter variations in Lf and Cf (i.e., non-linear load: 0%–100%)—First: Load output voltages (VL), Second: Load output currents (IL),

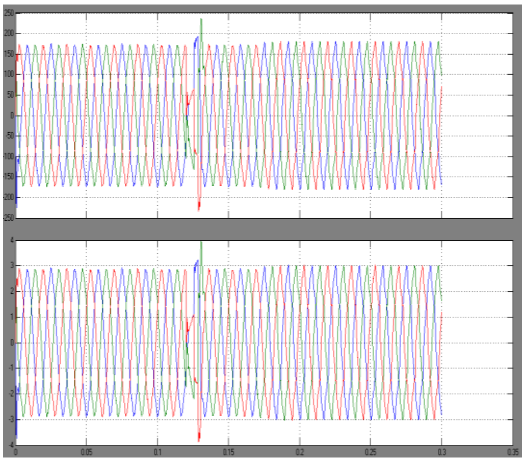

Fig. 4.3 Simulation and experimental results of the proposed observerbased optimal voltage control scheme under load step change with −30% parameter variations in Lf and Cf (i.e. balanced resistive load)First: Load output voltages (VL), Second: Load output currents (IL),

CONCLUSION

This paper has proposed a simple observer-based optimal voltage control method of the three-phase UPS systems The proposed controller is composed of a feedback control term to stabilize the error dynamics of the system and a compensating control term to estimate the system uncertainties. 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.

Furthermore, the proposed voltage control law can be methodically designed taking into account a tradeoff between control input magnitude and tracking error unlike previous algorithms. The superior performance of the proposed control system was demonstrated through simulations and experiments. Under three load conditions (load step change, unbalanced load, and nonlinear load), the proposed control scheme revealed a better voltage tracking performance such as lower THD, smaller steady-state error, and faster transient response than the conventional FLC scheme even if there exist parameter variations.

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