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Voltage Control Techniques in Uninterruptible Power Supply Inverters: a Review

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Abstract – *Uninterruptible power supply (UPS) systems are required for supplying sinusoidal output voltage for linear and nonlinear loads. They must be highly reliable and fast in dynamic response. Many control strategies have been applied to UPS inverters. The basic objectives of UPS control systems are tracking ability and robustness. Generally, the tasks of output voltage control for UPS inverters are providing fast dynamic responses and maintaining a perfect sinusoidal voltage waveform even with nonlinear or changing loads. To achieve these aims, many controllers have been proposed in the literature. In this paper a comprehensive review of the control techniques of UPS systems with advantages and disadvantages of each is carried out.*

***Keywords**: Inverter, Uninterruptible Power Supply, Control Techniques*

I. Introduction

The main objective of uninterruptible power supply (UPS) systems is to supply a sinusoidal voltage with constant amplitude and frequency to critical loads such as industry controllers, computer and communication systems without any interruption and irrespective of load and supply conditions [1], [2]. It is well known that the main control objective in an UPS inverter is the tracking of the delivered voltage towards a desired sinusoidal reference in spite of the presence of distorted loads [3], [4]. UPS systems can be classified as static, rotary and hybrid. Obtaining high performance, such as low total harmonic distortion (THD), good voltage regulation and quick transient response for sudden changes at load, is very important in such applications [5]-[8]. The block diagram of a typical on-line UPS inverter system is shown in Fig. 1.

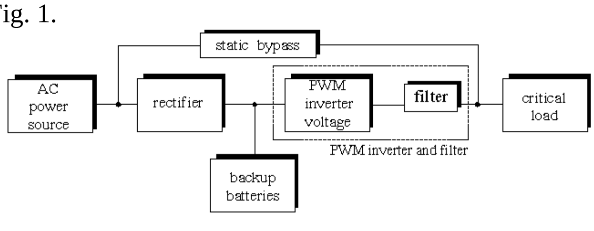

Fig. 1. Block diagram of a typical on-line UPS system

A rectifier is used for converting single-phase or three-phase alternating ac input into direct dc, which supplies both the battery bank for energy storage and voltage source inverter. A half bridge or full bridge pulse width modulation (PWM) inverter is used to convert a dc voltage to a low THD sinusoidal output, a battery to prove continuous source of electrical power and a power LC filter to reduce harmonics or ripple from the inverter output [6]-[12].

The UPS system has two operating modes. Without the input power, the static bypass switch is opened and the charger is disabled. The inverter operates in backup mode and supplies power to the load using the battery [7]. During the bypass mode, when the ac line is within the preset tolerance, most of the power is supplied directly from the ac line to the load. It typically operates with a PWM strategy under feedback control to realize the desired output voltage, which minimizes the filter cost, size, weight and loss. It is also used to overcome the voltage fluctuations of power system [8]. Some of the main objectives of UPS are [9], [10]: having high efficiency and reliability, providing a regulated sinusoidal output voltage with minimal THD, having sinusoidal input current with low THD and unity power factor over normal mode, wide input voltage fluctuations with constant output voltage, capability of smooth transfer from charging mode to backup mode at the power fault and low noise at the input and output terminals.

Different techniques and circuits have been so far recommended to improve UPS performance and obtain ideal specifications [11]-[19]. In [12] the design consideration and digital control technique of an on-line, low-cost, 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 three-phase UPS systems is proposed in [13]. In [14] 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

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base on linear control theory to control of the output voltage of three-phase UPS systems is proposed in [15], which the tracking control law is obtained with a pole placement technique.

A hybrid regenerative power system including photovoltaic and wind powers and combining the functions of the grid tie system and UPS for critical load applications is presented in [16]. A droop method based on proportional-resonant controller to control the power sharing of parallel UPS systems is presented in [17], which ensures good transient response and steady-state objectives. In order to obtain fast response in the current control in single phase UPS, the digital control scheme based on the instantaneous values is proposed in [18], where in the controller is constructed by a DSP.

In [19] inner-outer loop controllers are adopted to regulate output voltage and to improve system response, and a current weighting distribution control (CWDC) strategy is used in multi-inverter systems to achieve current sharing is presented. In [20] UPS system with two LC filters in the inverter output is analyzed and their effects on reducing the distortion in the output voltage is shown. The system model consists of the output filter, the control system and the single phase inverter. In [21] a model of UPS system has been introduced based on series and parallel combination of two full bridge voltage inverters where a series converter receives the input and a parallel converter is the load. Connected to wide applications of UPS systems have extended the control strategies to achieve performance and pure sinusoidal output voltage. Output impedance, transient response for nonlinear load and load changing, voltage regulation and THD factor are important operational parameters for a UPS system. Inverter provides a sinusoidal output voltage for nonlinear and discrete loads and the objective of the design of control system is to supply voltage for load variations. There are three non-lineararities in PWM voltage source inverters [22]: (1) the dead time derates the output voltage and the influence is dependent on the direction of phase current, (2) a ripple in the dc link voltage, due to the behavior of the rectifier, influences directly on the output voltage, and (3) the output drop across the switches influences the output voltage. Performance of a PWM is evaluated by THD factor; this factor expresses the reliability of the system. To develop a sinusoidal output voltage with low distortion in UPS system, a powerful controller is required for closed-loop regulation in inverters. In spite of existing high frequency switching devices, a good sinusoidal output voltage is realized using a PWM inverter with LC filter. The closed loop control has particular application in the UPS system. Varying load and non-ideal PWM inverter cause a problem of having a low THD factor for output waveform and simultaneously not having a good transient response [23]. A PWM technique used for eliminating the harmonic components cannot prevent the distortion of output voltage in the nonlinear loads. Control methods require similar data from parameters of the system. Also the switching frequency must be high. In the UPS applications, switching frequency is chosen tens of kHz that is very larger than natural and PWM inverter system modulation frequencies.

The harmonics lead to communication interference, excessive heating in capacitors and transformers, solid state device malfunctions, and so on. The main drawback of PWM inverter is the large size, considering nonlinear loads such as rectifier and triac loads. Nonlinear loads and parameter uncertainties, cause periodic tracking error, are major sources of THD in UPS system [24]. Multiple filters provide an alternative to minimize periodic error occurred in a dynamic system. In [25] describes the design procedure of the inverter output multi filter. With multi filter, the output voltage waveform can be sinusoidal under nonlinear load, no load or light load. This approach requires only sensing of the output voltage.

A typical control system is composed of four parts: a plant to be controlled, sensors for measurement, actuators for control action and a control law. Generally, the tasks of control systems can be divided into two categories: stabilization or regulation and tracking or servo. The basic tasks of the UPS control include: (1) load voltage magnitude and frequency regulation, (2) maintaining a sinusoidal voltage waveform at the load and (3) damping of output filter oscillations. Furthermore, for three phase UPS systems maintaining phase voltage balance and for parallel redundant UPS systems ensuring power sharing, should be considered [26]. To remove overall drawback, several techniques and different control strategies have been proposed in the literature as shown in Fig. 2 [27].

In this paper various control techniques to achieve both good dynamic response and low THD at output voltage of UPS inverter system are reviewed. The major difference between common objective from an advantages and disadvantages point of view are described. The paper is structures as follows. Section II presents a general review of classification control techniques. The learning feed forward controls such as repetitive control, instantaneous feedback controls such as deadbeat control and nonlinear controls such as sliding control are described in sections III, IV and V, respectively. Finally, this paper concludes with a brief outline of the adventages and disadvantages of various control strategies in section VI.

II. Classification Control Techniques

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

II.1. 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).

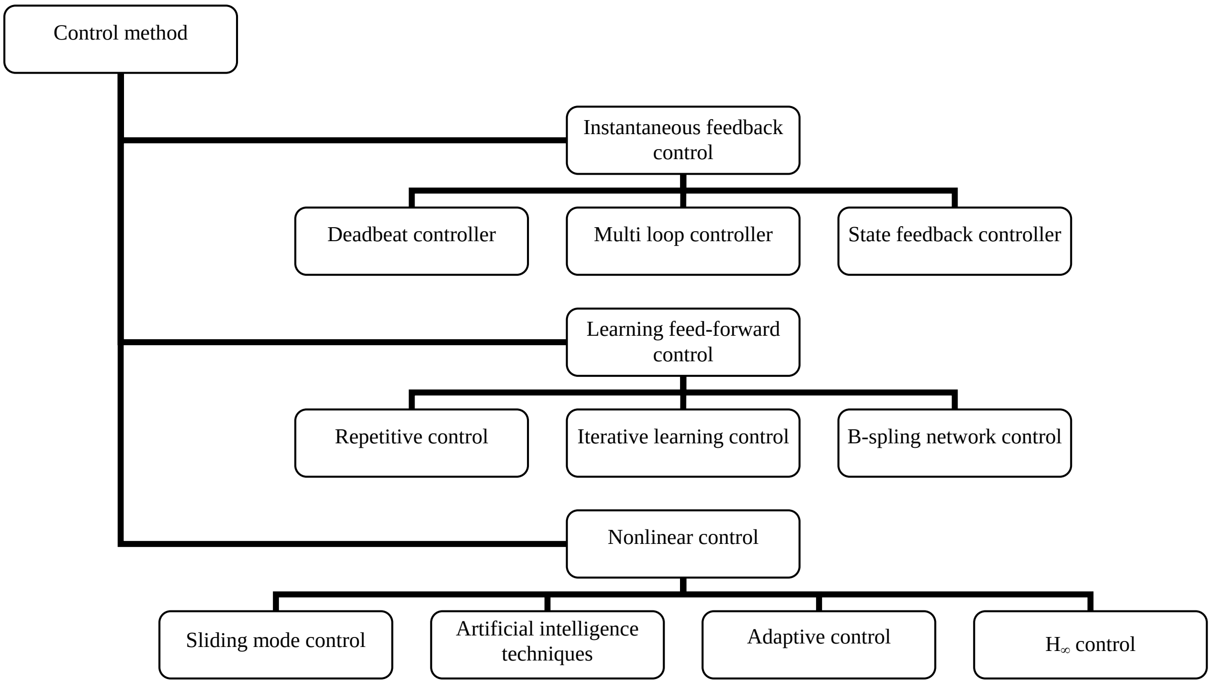

Fig. 2. A classification of control techniques for UPS inverter system

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 [10], [28]. In [29], 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 in [30], which the LQR parameters are calculated by minimizing a cost function.

II.2. Analog and Digital Control

The controllers can also be classified into two groups: analog based such as multiple feedback loops [31] and digital based such as deadbeat controller [32], [33]. Analogue techniques are used in continues approaches. Most of the analog based controllers were designed based on linearized model and traditional frequency domain analysis.

In designing a digital controlled PWM switching converter, two switching frequencies require careful selection: the PWM switching frequency of the power converter and the sampling frequency of the digital controller [34]. Various digital control schemes for UPS inverters have been proposed in last twenty years, including deadbeat control, repetitive control, digital multi loop control, and so on. There are many advantages for digital controllers, such as immunity to drifts, insensitivity to component tolerances, ease of implementation and changeable control law software updating. If the poles of a closed loop system of an analogue control system are far from s–plane, the system has a quicker dynamic response, but in the digital systems, all poles of the closed loop must be on the origin of z–plane [35].

II.3. Linear and Nonlinear Control

On the basis of design and analytic approach can be divided into two main groups: linear such as predictive control [36] and ramp comparisons current [37], and nonlinear such as the neural network [38], hysteresis current control [39], H_∞ control [40] and fuzzy logic control [41]. It appears that the nonlinear controller is more suitable than the linear type since the inverter is truly a nonlinear system. Various methods of current control can be used in UPS inverter to provide current protection, improve the performance of output voltage and to simplify parallel operation. The performance of current controller systems depends on the feedback control strategy used, which can be broadly categorized into linear and nonlinear systems [42].

III. Learning Feed-Forward Control

Feed forward is used to cancel the effects of known disturbances and provide prediction in tracking tasks. Learning control scheme is easy to implement and do not require exact knowledge of the dynamic model. In learning control, the controller is not designed on the basis of the process model. The controller is either trained based on the previously collected data or is trained during control. The learning feed forward control (LFC) acts as an add-on element to the existing feedback controller. In LFC there are two parameters B-spline support width and the learning gain to adjust [43]. A plug-in digital repetitive learning control scheme for three phase constant-voltage constant-frequency (CVCF) PWM inverter is present in [44]. Several feed forward control techniques have been proposed: modulated integral control [45], modified discrete control law [46], one cycle control [47], and so on. In [48], a reset integral controller was developed for a single phase UPS inverter by using one cycle control technique. This approach was particularly suitable for its robustness against large input voltage variations. However, the performance of the output voltage decreases when nonlinear load must to be supplied.

III.1. 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 [49]. 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.

Fig. 3 shows the block diagram of a repetitive controller for ac voltage regulation. A repetitive controller consists of three tracking controller (G_1), continual controller (G_2) and parameter tuning controller (G_3). 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 G_3 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 [50]. So far, many strategies have been employed for RC in industry. In [1], the RC has been combined with pole 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. In [51], 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. In [52], a repetitive learning controller is used to obtain high quality output waveform from an inverter feeding a non linear load. In [53] an adaptive repetitive control scheme that employs an auxiliary compensator to stabilize the closed loop system even with variations in the plant is presented. In [54], 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.

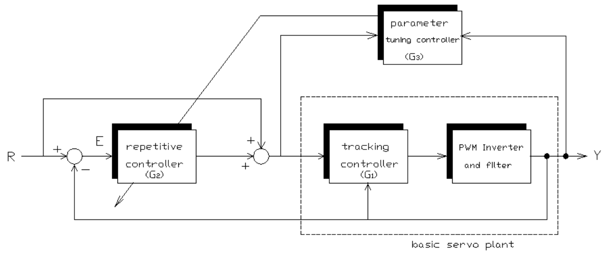

Fig. 3. Repetitive controller

III.2. 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 Fig. 4 is comprised of feed forward learning loop from previous learning cycle error and feedback learning loop from instant error.

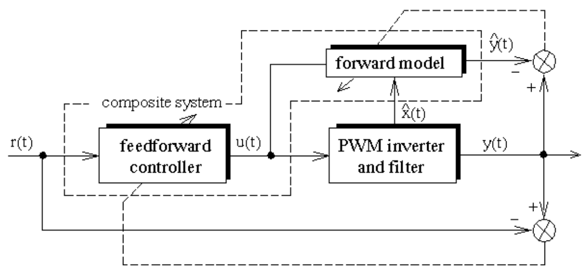

Fig. 4. Block diagram of iterative learning controller

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 [55]. A current regulation method based on iterative control technique is proposed in [56], in order to reduce the distortions caused by both the dead-time and the zero crossing problems. In [57] an 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.

III.3. B-Spline Network Control

Spline theory is used to solve problems associated with large amount of data or information needed to be described in a simple form. The B-spline functions can be used to smoothly fit the data given, and are widely used in the engineering fields. Local adjusting is easy and needs simple calculation and implementation [58]. B-splines functions are functions with minimum local supports in all splines functions. B-splines allow describing spline functions as linear combinations of weighted basis functions.

They are numerically stable and simplify the computation of spline functions. B-spline network control (BSN) is a specific realization of an associative memory network [59]. B-spline neural network is characterized by a local weight updating scheme with the advantages of fast convergence speed and low computation complexity. B-spline neural network is more suitable for real time applications [60].

IV. 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 [27]. Many fast response IFC strategies such as deadbeat control and cascade control have been developed for distinct applications to achieve zero steady state error and fast transient response which can occur under nonlinear loads.

IV.1. 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 [48], [61]. DTC strategies are mostly based on the deadbeat control (DBC) theory. DBC was introduced in the middle of decade 1980 [22], [62]. 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 [63].

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 against other inputs and has high sensitivity to the load change [64]. The technique of locating all poles of a discrete time system at zero equals DBC method. In [65], 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 [66], [67].

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. In [68], 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 in [69]. Fig. 5 shows basic block diagram for deadbeat controlled PWM inverter in UPS systems.

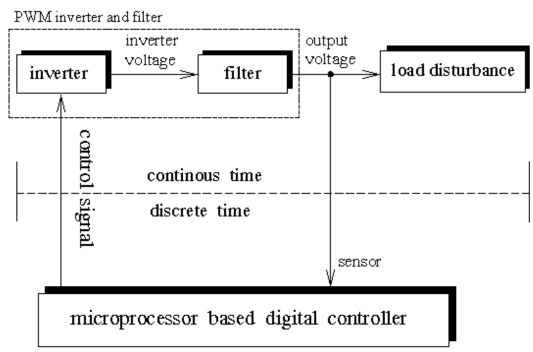

Fig. 5. Block diagram for deadbeat control of PWM inverter

IV.2. Multi-Loop Controller

The multiple feedback loop controller is simple and easy to implement. Using instantaneous feedback control results in sinusoidal input current and output voltage. The analogue control feature in UPS systems provides sinusoidal output voltage and input current with a high input power factor. This type of control has low reliability and regulation due to change of regulation parameters. In the feedback control technique of instantaneous voltage, the reference output waveform is adjusted by comparison of feedback voltage with sinusoidal reference.

In such a case, the dynamic characteristics are quickly improved, since only the voltage signal is controlled, it is not optimal for current change and nonlinear loads and multiple loop control is applied. Current mode control is basically a multiple loop control method in which the current negative feedback loop is commanded by the error signal of the outer voltage regulation loop. Current regulators can be implemented on an analog or digital platform [41]. Typical current regulators reported in the literature include hysteresis current control (HCC), predictive current control (PCC), adjacent state regulators (ASR), ramp comparisons control (RCC), SPWM current control, peak current mode (PCM) controllers and average current mode (ACM) controllers [70], [71], [72]. The advantages of ACM are constant switching frequency and improved noise immunity. HCC is simple in implementation, inherently limits the current and has a fast transient response, but the switching frequency depends on load characteristics and the hysteresis band [73]. Also, the gain of the hysteresis comparator is considered to be infinite and protection of the hysteresis controlled inverter is difficult owing to the random appearance of the gating signals [74]. PCC requires a good knowledge of load parameters, in addition to having the same calculation problem, but implementation of a practical system can be difficult and complex. RCC using a PI regulator has a long history of use, but has the disadvantage of steady state phase error between the target current and the output current, and also requires accurate tuning to suit load parameters. SPWM current control, is comparison to instantaneous current error with triangular waveform, not only maintains constant switching frequency but also provides fast dynamic response for UPS application [75].

Fig. 6 shows the system control diagram of the current mode technique for single phase voltage-source full-bridge inverter with a mono filter. The output voltage feedback is compared with a sine reference signal and the error voltage is compensated by a PI regulator to produce the current reference (I_R).

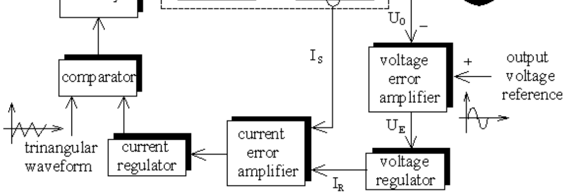

Fig. 6. Block diagram of current mode control with feedback

The instantaneous current control of inductance or capacitance filter (I_S) is sensed and compared with I_R. After compensated by a PI regulator, the error signal (U_E) is compared with a triangular waveform to generate SPWM signal for switching control of switches. The inductance current is the sum of capacitor and load currents and the load voltage is controlled in another closed loop [76]. The feedback reduces the system error; in addition, it influences band width, impedance, sensitivity and stability. In the advanced control system, three filter current signals are sensed as feedback in order to adjust the circuit current and output voltage, for regulating the load voltage and current and balance the load noises. In [77], a design of inverter using PWM technique with injecting harmonic to the three phase UPS systems, for changing dc bus voltage, has been proposed; and a control form with instantaneous voltage feedback and average voltage feedback for obtaining the static and dynamic characteristics have been presented. In [78], the inverter regulated current loop and output voltage balance have been suggested where an inner current circuit an external voltage circuit have been employed to make the produced un-damped poles ineffective by resonance circuit; the closed loop system will be stable, showing quick dynamic response. Also this paper has shown that the output current for feedback of UPS system with second–order load filter is not suitable. Here current or voltage of capacitor is used as the feed variable. The multiple loop control strategy which incorporates an outer voltage loop and an inner current loop is presented in [79], where inner current loop is added to regulate the output voltage of the PWM inverter. Also, the output voltage and load current compensation are added in the scheme to improve the performance and robustness of the system. The multi loop control (cascade control) with capacitor current inner loop and output voltage outer loop for a single phase half bridge UPS inverter is presented in [80]. In this approach, the transient performance of the controller totally depends on the high bandwidth of the inner loop, but the high gain of the controller would cause the closed loop system to be sensitive to noise.

IV.3. State Feedback Controller

To obtain a satisfying dynamic behavior of the closed loop system a state feedback applied in [81]. 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 [82]. In [83], a combination of state feedback control and repetitive control is proposed. This hybrid achieves excellent dynamics and low THD with non-linear loads, but the magnitude of the output voltage is subject to variations with load changes. In [80], 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. In [84], a robust state feedback control based on a linear matrix inequality design has been applied to a UPS system. In [85], repetitive control is combined with least square error (LSE) state feedback control, in the IFC scheme, serving as the inner loops.

V. 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 inverters [86]. In [87], 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 in [88], which it is shown that the proposed control scheme gives high dynamic responses at load variation as well as a zero steady-state error.

V.1. 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 designned 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 [89]. 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 [90], where the control force (U) is composed of two parts: a feed forward control force (U_F) and an SMC force (U_S).

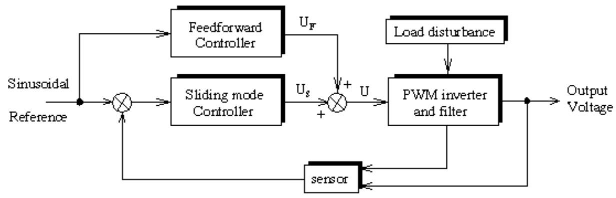

Fig. 7. Discrete feed forward sliding mode control scheme

The SMD design steps could be summarized as [91]: (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 in [92], 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 in [93] 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. In [94], 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.

V.2. Artificial Intelligence Techniques

Many Artificial intelligence techniques such as neural network and fuzzy system have been employed to improve the controller performance for a wide range of plants while retaining their basic characteristics.

a. Fuzzy logic control: The regulation characteristic of a fuzzy controller is different from the linear controller because the fuzzy logic control (FLC) is mostly nonlinear and makes a lot of adjustment possible. Most simple fuzzy feedback control systems contain a FLC in the form of a table of linguistic rules and input-output interfaces. FLC has the potential of operating successfully under a wide range of load variations since their working principles do not require precise knowledge of the load parameters [95]. FLC can handle nonlinearity and does not need accurate mathematical model. FLC is adaptive in nature which gives it robust performance under parameter variations and load disturbances [96]. A typical fuzzy process can be divided into four steps: the fuzzification, rule base, the inference mechanism and the defuzzyfication [97]. Fig. 8 shows a block diagram of fuzzy logic controller. The inputs of the fuzzy proportional-derivative (PD) controller are the error and the change of the error. The output of the fuzzy PD controller is the gain controller. A FLC is a synthesis of both, a controller loop and a set of linguistic rules which are the content of the decision element of the controller. FLC can work with less precise input. The algorithm is simple and it doesn't need advanced processor. It needs less data storage in the form of membership functions and rules compared to conventional look up table. The fuzzy controller is able to reduce both the overshoot and extent of oscillations and for improving the steady state response; the repetitive control as shown in Fig. 9 is used.

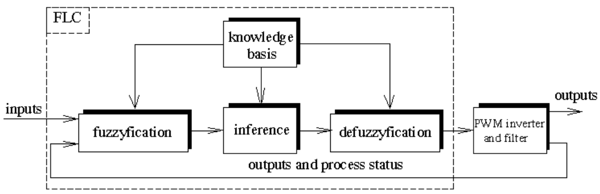

Fig. 8. Block diagram of the fuzzy logic controller

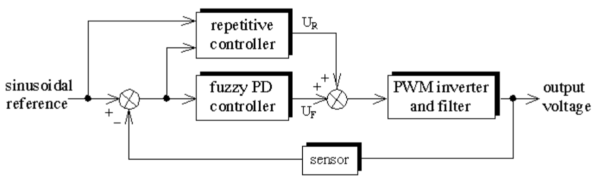

Fig. 9. Block diagram of the fuzzy-repetitive control

The fuzzy PD controller plays an important role in improving overshoot and rise time response during severe perturbations. A control system for UPS inverter includes double loop current mode control scheme in core and proportional-integral (PI) parameters of voltage control loop are adjusted using FLC presented in [98]. The hierarchical FLC scheme is employed for a single phase voltage source half bridge UPS inverter with second filter proposed in [79]. An approach for combining the deadbeat control and fuzzy logic compensator for real time digital of the single phase PWM UPS inverter is proposed in [99]. A hybrid fuzzy-repetitive control scheme for single phase CVCF is presented in [94]. An FLC and a digital PI control for the application in feedback control of a power factor corrected pre-regulator used in a high performance on-line UPS is proposed in [96].

b. Neural network controller: A neural network (NN) is an interconnection of a number of artificial neurons that simulates a biological system. When a NN is used in system control, the NN can be trained either on-line or off-line [37]. The main advantage of the NN is that it has excellent merit for nonlinear control and is adaptive enough to firing the environment change.

Fig. 10 shows the proposed artificial neural network (ANN) of a 5-3-1 structure controlled inverter. The inputs are the capacitor current, delayed capacitor current, the load current, the output voltage and the error between the reference voltage and the output voltage [100].

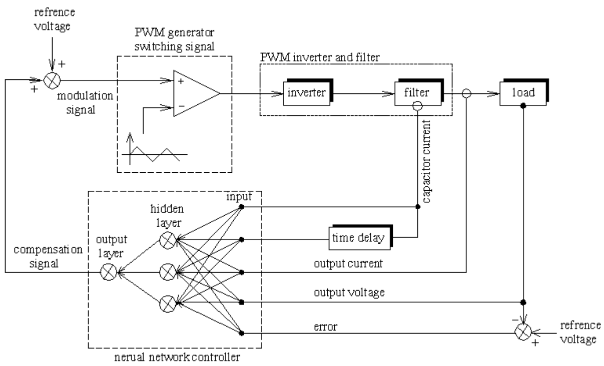

Fig. 10. Neural network control scheme for UPS inverter

The ability of the ANN to approximate nonlinear functions is most significant. A low cost analog ANN control scheme for UPS inverters with a selected ANN is trained off-line with the database comprising all example patterns is proposed in [101]. In [102] presented an ANN application in the harmonic elimination of PWM converters where the ANN replaced a large and memory demanding look-up table to generate the switching angles of a PWM converter for a given modulation index.

V.3. Adaptive Controller

The basic idea of adaptive control is to estimate the uncertain plant parameters online based on the measured system signals, using the estimated parameters in the control input computation. An adaptive control system can thus be regarded as a control system with online parameter estimation. The adaptive controllers are digital feed forward controllers containing gain coefficients that are updated by a learning process designed to optimize the controller response based on desired performance criterion.

The adaptive controller consists of two distinct parts: a feed forward control function which inputs load currents and voltages, and an on-line controller learning process which adjusts the feed forward controller gain coefficients with the objective of improving the controller performance. In [103], linear and nonlinear adaptive control strategies for a three phase UPS inverters are presented. An on-line adaptive learning algorithm is also described which promotes steady state controller stability.

TABLE I
A COMPARISON OF CONTROL TECHNIQUES

Control strategy	Advantage	Disadvantage
Multi loop control	- high robustness - ease of implementing	- more than two sensors are needed
Feed forward learning control	- require only sensing the output voltage	- transient performance is poor
Sliding mode control	- robustness and insensitive to parameter and load variations - fast dynamic response - simple implementation	- very high switching frequency - large number of state variable sensors
Fuzzy logic control	- intensive robustness - operating successfully under a wide range of load variation - explanations of results - fine tuning - simple structure	- very powerful processor - tolerance for ambiguity
Deadbeat control	- stable operation for disturbances and nonlinear load - very fast transient response - applicability to three-phase systems	- very sensitive to parameter and load variations - requires estimation of the load parameters - poor stability - requires a lager actuating signal to achieve the deadbeat effect - can be implemented by fast microprocessor
Repetitive control	- high quality sinusoidal output voltage	- very slow dynamic response - can be implemented by fast microprocessor
Neural network control	- can be trained either on-line and off-line - excellent merit for nonlinear control - generalization and learning ability -adaptive enough to fir the environment change	- tolerance for uncertainty - complex implementation
Instantaneous feedback control	- high quality output voltage - fast dynamic response	- more variables need to be sensed - high speed control is required

V.4. H_∞ Control

With the advances in the technology of microprocessors and digital signal processing, nonlinear digital control strategies such as H_∞ has been proposed for the control of UPS inverters. A key point in robust control is the definition of a suitable mathematical model of the uncertainties affecting the controlled plant [104]. The H_∞ control theory has been introduced in the early 1980s opening a new direction in robust control design. H_∞ control is able to theoretically take account of modeling errors, disturbances and system noises in design stage. The general configuration for H_∞ control is shown in Fig. 11, in which $\Delta(s)$ is output multiplicative uncertainty, $P(s)$ is the augmented plant obtained by appending the weighting function $W(s)$ to the output of the transfer function $T_{WU}(s)$ of the desired loop shapes. The symbol $T_{WZ}(s)$ denotes the closed loop transfer function from W to Z. The design goal is to synthesize the stabilizing controller $K(s)$ so that the H_∞ gain from W to Z is less than one. The advantages of this approach are reducing control circuit cost and simplified implementation, which requires only voltage feedback. An H_∞ loop shaping design for single phase UPS inverters to achieve sinusoidal tracking rather than set point regulation and good performance proposed in [39]. A robust controller based on the μ-synthesis for single phase UPS system is proposed in [9].

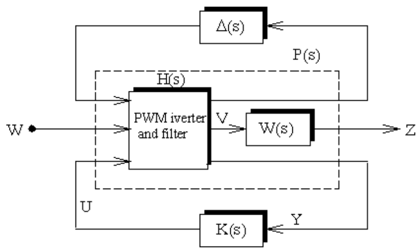

Fig. 11. Configuration of H_∞ control

VI. Conclusion

UPS systems are used in order to assure the continuity of supply for the critical loads. At the same time, good load regulation, fast transient load response and good switching frequency suppression is required. In most cases, the cost of control system increases with its complexity. In this paper some research has been carried out on the various control techniques of UPS inverter to achieve appropriate dynamic response and output voltage with low total distortion harmonic. Their advantages and disadvantages have been discussed. The multiple feedback loop controller requires a comprehensive analysis on both the open loop and closed loop frequency responses of the UPS inverter control system for various controller parameters. The dead beat control requires larger actuating signal to achieve the deadbeat effect and the performance of the system is sensitive to parameter and load variations. Also, control signal depends on a precise PWM inverter load model. The characteristics of several control techniques for UPS inverters and the advantages and disadvantages are summarized in Table I. Modern UPS control systems are implemented digitally, on control hardware built around one or more digital processors.

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