Nonlinear Control Techniques in Uninterruptible Power Supply Inverter: A Review

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***Abstract*— Summarizes the basic objectives of controllers for UPS system are tracking ability and robustness. To get this aims, many controllers have been proposed in the literature. In this paper a comprehensive review of the nonlinear control techniques of UPS systems with advantages and disadvantages are 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 us well know that the main control objective in a ups inverter is the tracking of the delivered voltage towards a desired sinusoidal reference in spite of the presence of distorted loads [3, 4]. A simplified classification scheme of the UPS system is 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. The block diagram of a typical UPS inverter shows in Fig. 1. A rectifier is used for converting single-phase or three-phase alternating ac input into direct dc, which supplied both the battery bank for energy storage and voltage source inverter. A half bridge or full bridge pulse width modulation (PWM) inverter used for to convert a dc voltage to a low THD sinusoidal output, a battery to proved continuous source of electrical power and power LC filter used to reduce harmonics or ripple from the inverter output [5]. The UPS system has two operating modes. With loss of 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. 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 operated with a PWM strategy under feedback control to realize the desired output voltage, which minimizes the filter cost, size, weight and loss. They also used to overcome the voltage fluctuations of power system [6]. The features of an ideal UPS consist of [7]: (1) Having high efficiency and reliability, (2) Providing a regulated sinusoidal output voltage with minimal THD in normal and backup modes. There is even such a case for non linear loads and unbalanced case, (3) Low cost and weight and small size and free–maintenance, (4) Having sinusoidal input current with low THD and unity power factor over normal mode, neglecting the load power factor and non linearity, (5) Wide input voltage fluctuations with constant output voltage, (6) Capability of smooth transfer from charging mode to backup mode at the power fault, (7) Low noise at the input and output terminals.

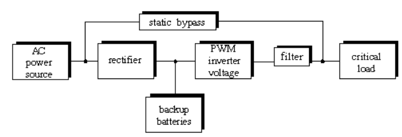

Figure 1. Block diagram of conventional UPS system

Different techniques and circuits have been so far recommended to improve UPS performance and obtain ideal specifications. In [8] 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 flyback 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. In [9] inner-outer loop controllers are adopted to regulate output voltage and to improve system response, and a current weighting distribution control (CWDC) strategy for multi-inverter systems to achieve current sharing is presented. In [10] UPS system with two LC filter in the inverter output is analyses and their effects on reducing the distortion in the output voltage are shown. The system modeled consists of the output filter, the control system and the single phase inverter. A wide application of UPS systems enhances the control strategies in order to achieve a good 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 UPS system. Inverter provides a sinusoidal output voltage for nonlinear and discrete loads and the objective of the design of control system is supplying voltage for load variations [11]. There are three non-lineararities in PWM voltage source inverters [12]: (1) the dead time derates the output voltage and the influence is dependent on the direction of phase current, (2)

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a ripple in the dc link voltage, due to the behavior of the rectifier, will influence directly on the output voltage, and (3) the output drop across the switches will influence 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 [13]. To remove overall drawback, several techniques and different control strategies for UPS inverter in the literature as shown in Fig. 2 have been proposed. 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 [14].

In this paper various control techniques for the UPS inverter system to achieve both good dynamic response and low THD at output voltage is reviewed, and the major difference between common objective from an advantages and disadvantages point of view are described. The paper is structure as follows. Section II presents a general review of classification control techniques. The nonlinear control such as sliding controller is describes in sections III. Finally, this paper concludes with a brief outline of the advantage and disadvantage of various control strategies in section IV.

II. CLASSIFICATION CONTROL TECHNIQUES

Based on aim of control system, different feedback control schemes for UPS inverters are classified.

A. Continuous-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 [7, 15]. In [16], 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 proposed in [17], which the LQR gains are calculated by minimizing a cost function.

B. Analog and Digital Control

The controllers can also be classified into two groups: analog based such as multiple feedback loops [18] and digital based such as deadbeat controller [19]. 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 frequency requires careful selection: the PWM switching frequency of the power converter and the sampling frequency of the digital controller [20]. 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 digital controllers, such as immune to drifts, insensitive 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, 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 [21].

C. Linear and Nonlinear Control

The controllers on the basis of design and analytic approach can be divided into two main groups: linear such as predictive control and ramp comparisons current, and nonlinear such as the neural network, hysteresis current control, H_∞ control and fuzzy logic. 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 over current protection, to improve the performance of output voltage controller and to simplify parallel operational. The performance of current controller systems depends on the feedback control strategy used, which can be broadly categorized into linear and nonlinear systems [22].

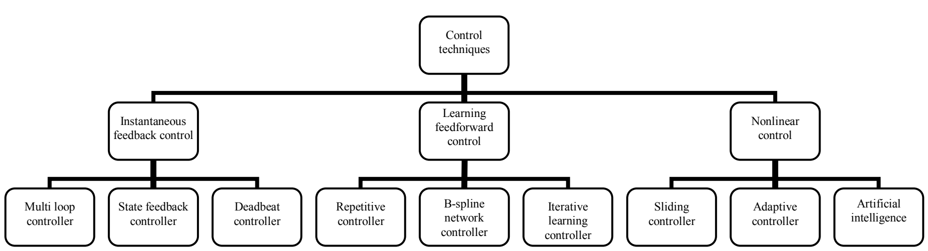

Figure 2. Classification control techniques for UPS inverter system

III. NONLINEAR CONTROL

The Nonlinear controller has a 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 important 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 this control technique to low power single phase UPS inverters [23].

A. 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 movement of system on the sliding level must reach a stable point corresponding to the required voltage and current. This method provides a systematic balance for preserving the stability. This method is not sensitive to the variation of the parameter of the system and external disturbances. The main problem with this method is the system indifferent on 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 a switch that produces a large amount of noises with high frequency and THD will be high [24]. Feed controllers gain which is generally constant, varies in respect to the state variables in the SMC. Fig. 3 shows the discrete feed forward SMC scheme [25], where the control force (U) is composed of two parts: a feed forward control force (U_F) and a SMC force (U_S). The SMD design steps could be summarized as [26]: (1) propose the sliding surface, (2) verify the existence of a sliding mode and (3) analyze 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 [27], 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. A SMC is proposed in [28] that periodic disturbance signal is added to make a pulse by 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.

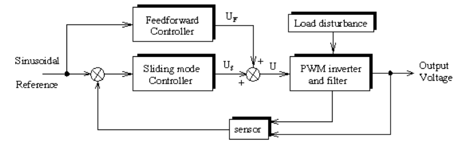

Figure 3. Discrete feed forward sliding mode control scheme

B. 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. The 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 variation since their working principles do not require precise knowledge of the load parameters [29]. FLC is a kind of digital control system with closed loop feedback and its essence is fuzzy controller. FLC can handle nonlinearity and does not need accurate mathematical model. FLC is adaptive in nature that gives it robust performance under parameter variation and load disturbances. A typical fuzzy process can be divided into four steps: the fuzzification, rule base, the inference mechanism and the defuzzyfication. Fig. 4 shows a block diagram of fuzzy logic controller. The inputs of the fuzzy proportional-divertive (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 function and rules than conventional look up table. The fuzzy controller is able to reduce both the overshoot and extent of oscillations and for improve the steady state response; the repetitive control as shown in Fig. 5 is used.

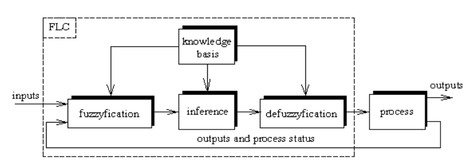

Figure 4. Block diagram of the fuzzy logic controller

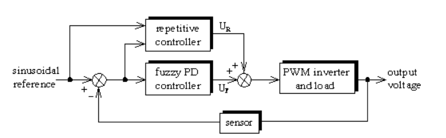

Figure 5. Block diagram of the fuzzy-repetitive control

The fuzzy PD controller plays an important role in improving an overshoot and a 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 [30]. 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 [31]. A hybrid fuzzy-repetitive control scheme for single phase CVCF is presented in [29].

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 [32]. The main advantage of the NN is that it has excellent merit for nonlinear control and is adaptive enough to fir the environment change. Fig. 6 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 [33]. 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 where is trained offline with the database comprising all example patterns proposed in [34].

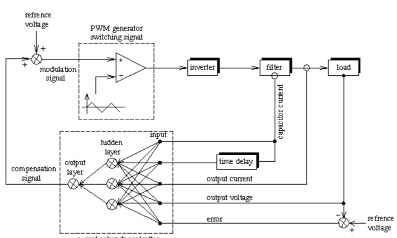

Figure 6. Proposed neural network control scheme for UPS inverter

C. Adaptive Controller

The basic idea adaptive control is to estimate the uncertain plant parameters online based on the measured system signals and use 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 is a digital feed forward controller containing gain coefficients that are updated by a learning process designed to optimize the controller response to a 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.

D. 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 [35]. The H_∞ control theory has been introduced in the early 1980 and open a new direction in robust control design. H_∞ control can be possible to theoretically take account of modeling errors, disturbances and system noises in design stage. The general configuration for H_∞ control is shown in Fig. 7, in which Δ(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 advantage of this approach is reduce control circuit cost and simplify in implementation, because 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 [36]. A robust controller based on the μ-synthesis for single phase UPS system is proposed in [6].

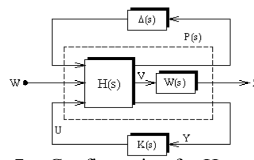

Figure 7. Configuration for H_∞ control

IV. CONCLUSIONS

UPS systems are used in order to be assuring 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 nonlinear control techniques of UPS inverter to achieve good dynamic response and output voltage with low total distortion harmonic. Their advantages and disadvantages have been discussed. The characteristics of the several control techniques for UPS inverter of view the advantage and disadvantage are summarized in table I.

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TABLE I. CONTROL TECHNIQUES COMPARATIVE

Control strategy	Advantage	Disadvantage
Sliding mode control	- robustness and insensitive to parameter and load variations - fast dynamic response - simple implementation	- very high switching frequency - high count of state variable sensors
Fuzzy logic control	- intensive robust - operating successfully under a wide range of load variation - explanations of results - fine tuning - simple structure	- very power full processor - tolerance for ambiguity
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 of implementing

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