

## A Simple Predictive Pwm Voltage Controlled Technique for Implementation of Single Phase Inverter with Precesion Rectifier

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### Abstract

A single-phase PWM inverter is presented to alleviate harmonic components of the output voltage and the load current. To keep the output voltage being sinusoidal and to have the high dynamic performances even in the cases of load variations and the partial magnetization in filter inductor, the modified digital predictive controller is designed and implemented on a prototype. The validity of the proposed inverter is verified through experiment. Additionally, low-ripple sinusoidal-current waveforms are generated with almost unity power factor. To assess the proposed inverter, it is compared with the conventional single-phase PWM inverter under the conditions of identical supply dc voltage and switching frequency.

**Keywords**—PWM inverter, predictive control, single phase, load current, output voltage, harmonics

### I. INTRODUCTION

PWM inverters can control their output voltage and frequency simultaneously. And also they can reduce the harmonic components in load currents. These features have made them power candidate in many industrial applications such as variable speed drives, uninterruptible power supplies, and other power conversion systems. However, the reduction of harmonic components in output currents is still the focus of major interest to alleviate the influences of electromagnetic interferences or noise and vibrations. Current harmonics produced by non-linear loads, such as switching power supplies and motor speed controllers, are prevalent in today's power systems. These harmonics interfere with sensitive electronic equipment and cause unnecessary losses in electrical equipment. In recent years we have witnessed the introduction of a new family of control schemes for inverters that runs under the heading of current controlled techniques. An efficient inverter should have some standard characteristics. These characteristics are summarized as:

- Simple and Robust
- Constant switching frequency
- Less calculations
- Fast operation with less sampling delays and
- Operation is independent on system parameters.

Many control techniques are presented by different authors. These control techniques can generally be classified as hysteresis, ramp comparison, and predictive current control [1]. Ramp comparison control using a PI regulator has a long history of use, but has the disadvantages of a steady state phase error between reference current and the output current, and also requires accurate tuning to

suit load parameters [1]. Hysteresis current controllers, presented in [2],

utilize hysteresis in comparing load currents to the references. Hysteresis current controllers have the advantage of simplicity and robustness, but the converters' switching frequency largely depends on the load parameters and consequently the load current harmonics ripple is not optimal. Improved hysteresis control strategies were proposed, including in [3] and in [4] which presented the variable-hysteresis-band current control technique. This control method, where the band is modulated with the system parameters, maintains a nearly constant switching frequency. However, its current ripple is still not optimal. Switch status dependent inner bound current control strategy [5], where an adaptive inner bound is modulated to reduce switching frequency while maintaining the current error within a specified bound. Predictive controllers calculate the inverter voltages required to force the measured currents to follow the reference current [6], [7]. This method offers the potential for achieving more precise current control with minimum distortion and harmonic noise; however, it needs more calculations and requires a good knowledge of the system parameters. The implementation of predictive strategies into digital controllers has been of particular interest in recent studies. The digital predictive current controllers for single-phase and three-phase voltage-source inverters are proposed [7]. This method fully compensates for the computational and sampling delays errors but the controller has a poor robustness in real system and the DSP processor cost is somewhat higher. The predictive controllers need good knowledge of the system parameters. If there are model mismatch in the control system, the mismatch will influence the control accuracy. In all these works the switching

states are changed at equidistant time instants. Although the switching frequency is limited to half the sampling frequency, the load voltage spectrum is spread over a wide range of frequencies. This is not desirable in some cases. The problem of spectrum is avoided by choosing an appropriate filter [8]. The robust DSP based current controlled method is proposed in [9], but in this method controller takes action before the period  $10\mu\text{s}$  of next cycle start and it need average value of grid voltage to find output voltage, which increases the calculation burden of controller. Also the DSP controller used is of high cost.

The authors propose an efficient low cost digital current controller for single phase inverter which overcomes the problems present in existing systems. This is an extension of [9]. The proposed technique uses new switching technique and low cost DSP starter kit to achieve all the characteristics of standard inverter. Experimental results demonstrate the superiority of the proposed method over existing methods.

## II. SYSTEM MODEL

The power circuit of the conventional converter considered is shown in Fig. 1. It consists of a dc voltage source, four power switches and a filter inductor. The full-bridge inverter's operation can be divided into four modes: two modes in positive load current period and two modes in negative load current period. Table 1 shows the single-phase grid connected inverter's operational modes.

$$S_a = \begin{cases} 1, & \text{if } S1 \text{ on and } S4 \text{ off} \\ 0, & \text{if } S1 \text{ off and } S4 \text{ on} \end{cases} \quad (1)$$

$$S_b = \begin{cases} 1, & \text{if } S_2 \text{ on and } S_3 \text{ off} \\ 0, & \text{if } S_2 \text{ off and } S_3 \text{ on} \end{cases} \quad (2)$$

### A. Basic Current Controller of Voltage Source Inverter

For inverter-based distributed generation systems (DG), the inverters are connected to the existing grid, therefore, the voltage cannot be controlled. The power quality is defined by the current quality. Pulse width modulation (PWM) is the most popular control technique in voltage-source inverters. As compared to the open loop voltage PWM converters, the current-controlled PWM has several advantages. One of the advantages is control of instantaneous current waveform and high accuracy. This advantage can control precisely the current injected into grid with low distortion and harmonic noise.

The strategies of current controllers can be classified as: ramp comparison controllers, hysteresis controllers, and predictive controllers. The ramp

comparison controller compares the current errors to triangle wave to generate the inverter firing signals. The hysteresis controllers utilize some type of hysteresis in the comparison of the currents to the current reference. The predictive controllers calculate the inverter voltages required to force the measured currents to follow the current reference.

### B. Traditional Predictive Current Controller

In [7], Holmes and Martin have proposed an algorithm for directly implementing a predictive current controller in a micro-processor for load situation where the load voltage is known. The proposed method compensates the errors caused by digital sampling and computing delays. The algorithm uses the results of previous switching cycles to estimate both the next grid voltage and load current. Fig. 1 illustrates the circuit diagram of single-phase grid-connected inverter. The inverter load current  $I_{load}$  is decided by following differential equation:

$$V_{op} = V_{grid} + L \frac{di}{dt} \quad (3)$$

Where  $V_{grid}$  is the grid voltage,  $V_{op}$  is the inverter's output voltage, and  $L$  is the filter's inductance. For the next switching cycle  $[n, (n+1)]$  above equation can be written as:

$$V_{op\_av}[n] = V_{grid}[n] + L \frac{I_{load}[n+1] - I_{load}[n]}{T} \quad (4)$$

The target of the controller is making the load current at  $[n+1]$  sample  $I_{load}[n+1]$  is equal to the reference current value at the end of switching period  $[n, (n+1)]$   $I_{ref}[n+1]$ .

To predict,  $V_{grid\_av}[n]$ , the average grid voltage over switching period  $[n, (n+1)]$ , assume that the change of grid voltage over the switching period is linear and the grid voltage change over the switching period  $[n, (n+1)]$  is equal to the change of the switching period  $[(n-1, n)]$ . Then,  $V_{grid\_av}[n]$  can be estimated from previously measured voltage using a simple linear extrapolation

$$V_{op\_av}[n] = \frac{5}{2} V_{grid}[n-1] + \frac{3}{2} V_{grid}[n-2] \quad (5)$$

### C. Robust DSP Based Predictive Current Controller

In [9] Hossein Madadi Kojabadi, Idris A. Gadoura, Liuchen Chang and Mohsen Ghribi proposed a DSP based predictive current controlled technique which is the modification of traditional current controlled technique. This predictive current controlled technique does the computations before  $10\mu\text{s}$  of switching period  $[n, (n+1)]$ . With this assumption, the measured values of current  $I_{load}[n]$  and grid voltage  $V_{grid}[n]$  are available up to instant

[n] before the calculation proceeds to predict the demanded output voltage of the inverter.

To predict  $V_{grid\_av}[n]$ , the average grid voltage over switching period [n, (n+1)], assume that the change of grid voltage over the switching period is linear and the grid voltage change over the switching period [n, (n+1)] is equal to the change of the switching period [(n-1), n]. Then, can be obtained from the measured grid voltage,  $V_{grid}[n]$ ,  $V_{grid}[n - 1]$ , as

$$V_{op\_av}[n] = 1.5V_{grid}[n] + 0.5V_{grid}[n - 1] \quad (6)$$

$I_{load}[n]$  can be estimated by adding the predicted current change during the switching period [(n-1), n] to the measured current at time [n-1]

$$I_{load}[n] = I_{load}[n - 1] + \frac{T}{L} \times \left[ \begin{matrix} V_{op\_av}[n - 1] - \\ \frac{3}{2}V_{grid}[n - 1] - V_{grid}[n - 2] \end{matrix} \right] \quad (7)$$

Substituting (7) and (6) into (4), the predictive average output voltage of the inverter over the switching period [n, n+1] can be obtained.

#### D. Proposed Modified Predictive Current Controller

The predictive current control techniques mentioned in above works shows that more calculations are required to find average output voltage and load current because for the prediction of next duty cycle continuous measurement of AC voltage samples are required. The robust predictive control technique in [9] generates reference sine/saw-tooth waveform externally. It required lot of tuning.

Also the output voltage variation spectrum is wide in above mentioned schemes because the next duty cycle prediction is allotted from 1% to 90% first by the prediction of load status, but as the load changes suddenly the system prediction get fails.

The purpose of the scheme is to generate the reference sine waveform internally using the look up table in DSPIC33fj16gs504 controller. This reduces the tunings. By using the simple linear AC-DC converter at the output of inverter to get the DC values equivalent to output AC voltage. Based on the DC voltage spectrum the duty cycles are adjusted to minimize the current harmonics. So, the calculations to find average output AC voltage is not necessary. The power circuit for the proposed modified predictive current controlled scheme is show in Fig. 1.

As illustrated in Fig. 2 the 230 V A. C. output of inverter is converted to the equivalent 2.5 V D.C. A threshold of 0.2V is given for regulation of A.C. voltage from 220 V to 240 V approximately.

### III. EXPERIMENTAL RESULTS

In order to validate the proposed scheme, experimental results with 500W, 700W and 1KW inverter is performed. The parameters used in the implementation are DC link voltage  $V_{DC} = 370V$ ,  $L = 2mH$ ,  $T_s = 50mS$ . The modified predictive control is implemented using a DSPIC33fj16gs504 starter kit.

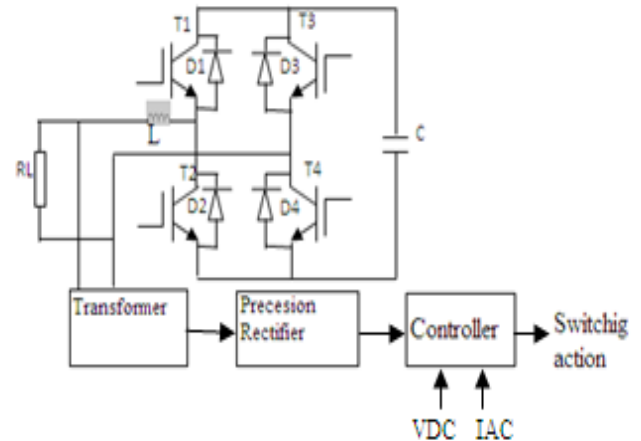


Fig. 1. Modified power circuit of single phase voltage source inverter.

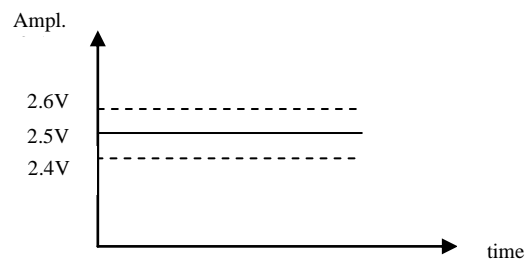


Fig. 2. Precision rectifier output.

TABLE I. INVERTERS OPERATIONAL MODES

Mode	Switch Position					Vop	Iload
	T1	T2	T3	T4			
1	on	off	off	on	+vdc	pos	
3	off	on	on	off	-vdc	neg	

The DC link voltage is 370 V. The normal grid voltage is 230 V and grid frequency is 50 Hz. The inverter is equipped with software and hardware protections including the over-current of dc link and inverter output, the over-temperature of IGBTs, the over-voltage of grid, dc link and generator, the under-voltage of grid and generator, the over-frequency of grid, and the under-frequency of grid.

Fig.3. Shows the inverter output current and voltage waveforms at 500W. It shows the harmonics present in current waveform is somewhat adequate. As load increases the percentage of harmonics

reduces one can recognize from the Fig. 4 and Fig. 5 at 700W and 1kW respectively. The current harmonics reduces and the AC current and voltage waveform become sharp compared to the less load.

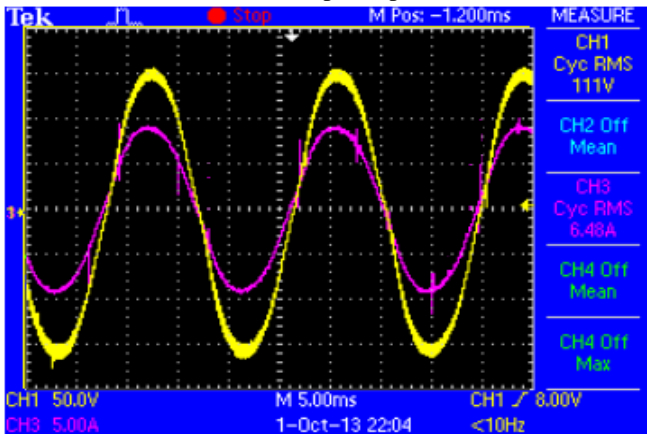


Fig. 3. Inverter output current and voltage at 500W

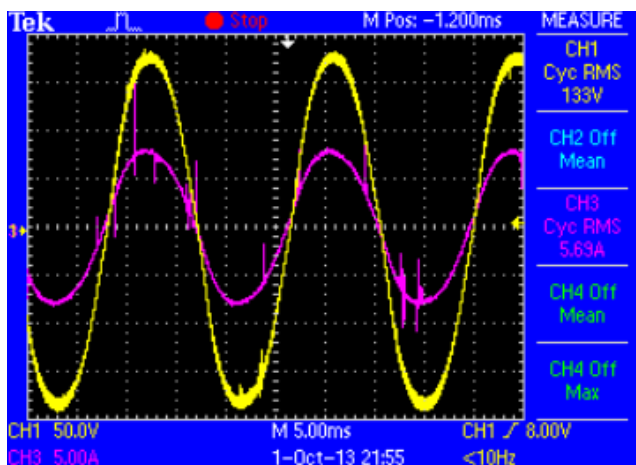


Fig. 4. Inverter output current and voltage at 700W.

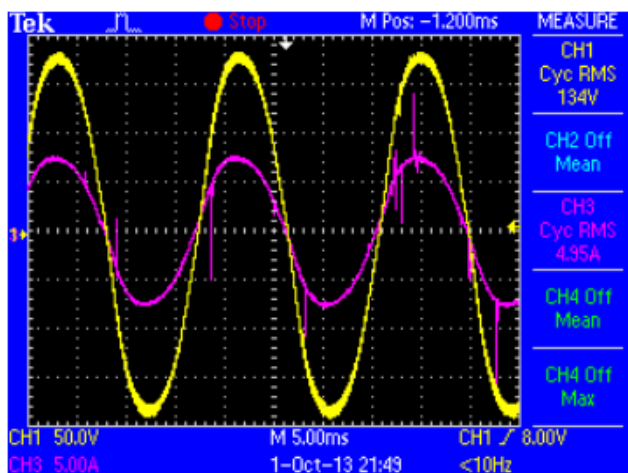


Fig.5. Inverter output current and voltage at 1KW.

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