A NOVEL CONTROL STRATEGY FOR POWER FACTOR CORRECTIONS BASED ON PREDICTIVE ALGORITHM

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***Abstract* – A novel control strategy based on predictive control for continuous conduction mode boost converter operating as a power factor correction is presented in this paper. Two horizons of the circuit behavior are predicted in the proposed algorithm which improves the total harmonic distortion, and especially reduces the low frequency harmonics. The algorithm doesn't need complex calculations, hence it is possible to implement this controller by cheap processors. Furthermore, an extra horizon of the prediction can expand the calculation time. Reduction of the input current harmonic distortion and improvement of the power factor are demonstrated on an isolated boost PFC converter.**

***Keywords* – Isolated boost converter, power factor correction (PFC), predictive control, total harmonic distortion (THD).**

I. INTRODUCTION

The input stage of the most consumer or industrial electronic equipments is an AC/DC converter. The simplest AC/DC converter is a diode rectifier with a capacitor filter, which acts as a nonlinear load and injects harmonics into the power system. Different standards have defined limits for line harmonics, such as IEEE/ANSI 519 or IEC61000-3-2. The power factor correctors (PFC) have been introduced to improve the input power factor and satisfy the AC line harmonic standards. The PFC converters for high power consumers are commonly designed for continuous conduction mode (CCM) because this method injects less harmonic into the line in comparison with discontinuous conduction mode (DCM) and have lower switch stress [1]-[4].

The conventional control block diagram of a PFC converter is composed of an inner line current control loop and an outer dc-link voltage control loop [2]-[4]. The inner current controller forces the input inductor current to follow the reference current, which is proportional to the rectified input voltage in order to achieve unity power factor. The outer voltage control loop provides a regulated output voltage by determining proper input current amplitude. Often a PI controller is used for the voltage regulation, but a fast and accurate controller should be used for the current controller to decrease the harmonic distortion of the input line [2], [3].

Nowadays digital controllers are preferred because of advantages of digital controllers over analog controllers. The digital controllers offer potential advantages of lower sensitivity to parameter variations, flexibility and possibilities to improve performance using more advanced control schemes [2]. Different current control schemes have been introduced to control PFC converters such as hysteretic control, average current control, peak current control and valley current control [2], [3]. Different predictive algorithms have been proposed to control the inner current control loop, because of its ability in nonlinear systems control, simple calculations and fast response. Many predictive controllers are based on valley current control strategy, which increase the low frequency harmonics [2], [3].

In this paper a predictive control strategy based on average current control method is presented, which controls an isolated boost PFC. Figure 1 describes the control block diagram and topology of the isolated boost PFC in details. This topology provides both step up conversion and galvanic isolation in one stage in order to increase the efficiency. For digital control implementations, the bandwidth is limited by the computational and sampling delays [4]. Therefore an extra horizon of prediction has been proposed which expand the calculation time. Thus it is possible to implement this control method by a cheap processor in spite of the fast changes in the input current waveform. The novel average current predictive control method improves the total harmonic distortion (THD) of the input current.

II. PROPOSED PREDICTIVE CONTROL ALGORITHM

The valley and average current control methods have presented in this section. Also a two horizon prediction algorithm based on average current control method has

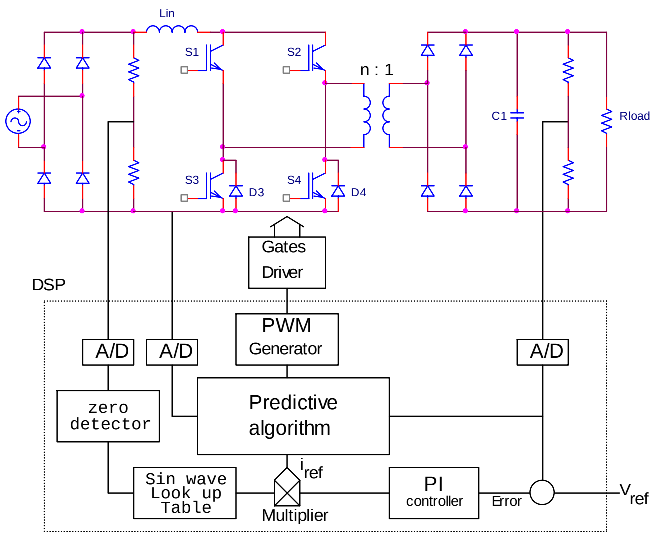

Fig. 1. Block diagram of predictive controller implemented on isolated boost PFC

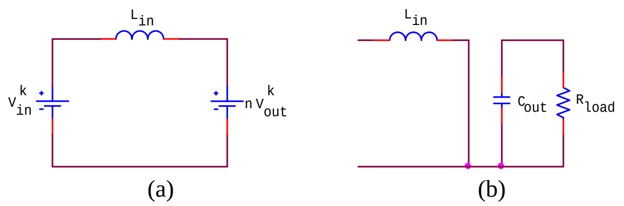

Fig. 2. Boost PFC circuit: (a) inductor is connected to output capacitor (b) input is short circuit trough inductor

proposed. These predictive algorithms are based on the following assumptions:

1- PFC operates in continuous conduction mode.

2- The switching frequency is much higher than the line frequency.

3- The reference current change within one period of switching is negligible in comparison with the input current ripple.

The equivalent circuits in both shoot through and energy transferring modes of the isolated boost converter where all components are referred to the primary side have been illustrated in Figure 2. In order to avoid the complexity, ideal models for the isolating transformer, input inductor and switches have been used. One should be considered is leakage inductor which generates voltage impulse. The treatment of this problem is outside the scope of this paper. The state equations can be expressed as follows:

$$L\frac{di_L}{dt} = V_{in} \qquad t^k \le t < t^k + d^k T_s \tag{1}$$

$$L\frac{di_L}{dt} = V_{in} - nV_{out} \qquad t^k + d^k T_s \le t < t^{k+1} \tag{2}$$

Where d^k is the k^{th} duty cycle. The input inductor current at the beginning of the next switching cycle can be derived from equations (1) and (2) as:

$$i_L^{k+1} = i_L^k + \frac{V_{in}^k T_s}{L} - \frac{nV_{out}^k T_s(1-d^k)}{L} \tag{3}$$

A. Valley Current Control method

In this algorithm the valley of input current follows the reference current. The input current waveform under valley control at one switching cycle can be seen in Figure 3. Predictive algorithm using valley strategy, equates the estimated inductor current at the end of the switching period to the reference current, in order to determine the duty cycle.

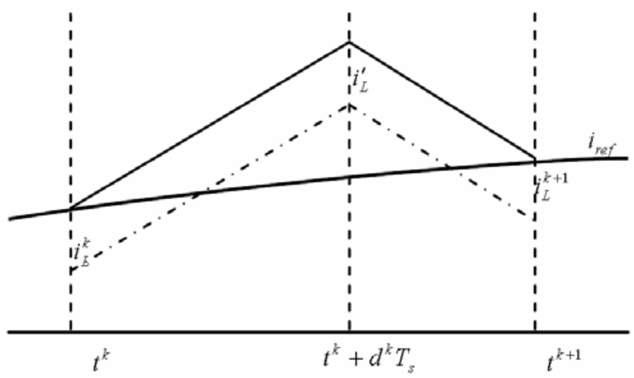

Fig. 3. Reference current and input current waveform of PFC in valley (line) and average (dot line) control strategy

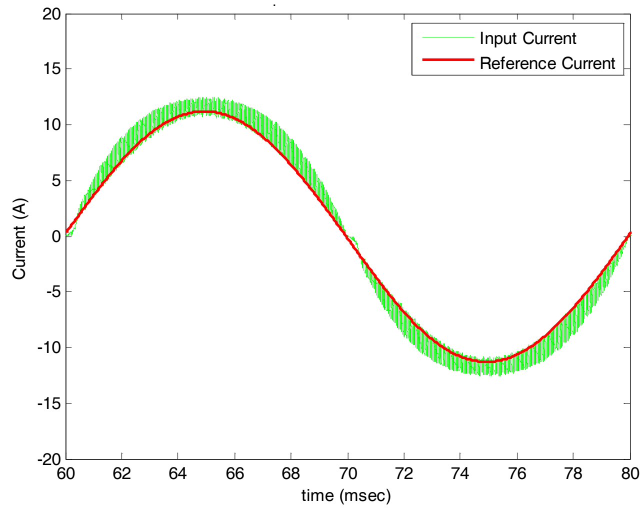

Fig. 4. The input current in valley current control strategy

Then k^{th} duty cycle can be calculated from (3) as:

$$d^k = \frac{nV_{out}^k - V_{in}^k}{nV_{out}^k} + \frac{L \times (i_{ref}^{k+1} - i_L^k)}{nT_s V_{out}^k} \tag{4}$$

In order to study the operation of control strategies, the isolated boost PFC converter including the controller has been simulated using the SIMULINK®. The PFC parameters which used in simulations are given in table I.

TABLE I
PFC Parameters

Parameter	Symbol	Value
Half switching cycle	T_s	50 μs
Transformer ratio	n	0.6
Input voltage	V_{in}	220 V(rms)
Output voltage	V_{out}	650 V
Output capacitance	C_{out}	760 μF
Input Inductance	L	2 mH
Load resistance	R_L	210 Ω

Figure 4 shows the input current waveform of the isolated boost PFC under valley control method at one period of line frequency. In an ideal controller the average value of the inductor current in every switching cycle should follow the reference current. Hence, there is an approximation in this predictive algorithm. If the inductor current ripple is negligible in comparison with the amplitude of sinusoidal input current, the valley control algorithm will work well. But, in order to reduce the cost and weight, it is preferable to use a smaller inductor, which leads to higher input current ripple. The harmonic spectrum of the input current is depicted in Figure 9. As can be seen, the valley current control strategy increases the low frequency harmonics (especially third harmonic).

B. Average Current Control method

In order to reduce the low frequency harmonics of the valley control method, the average control method is used. The goal of this method is to determine the duty cycle which equates the input current average over one switching period to the reference current. The average of input current over one switching period can be written as:

$$d^k\left(\frac{i_L^k + i'_L}{2}\right) + (1-d^k)\times\left(\frac{i_L^{k+1} + i'_L}{2}\right) = i_{ref}^k \tag{5}$$

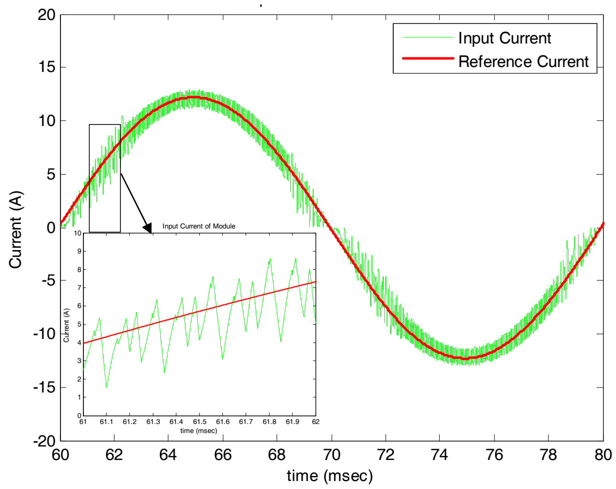

Fig. 5. The input current in average current control strategy

Where i'_L , i^k_L and i^{k+1}_L as shown in Figure 3, are current peak over switching period and the current at the beginning and end of switching period respectively. The i^k_L and i^{k+1}_L can be calculated from (1) and (3) as:

$$i'_L = i^k_L + \frac{V^k_{in} d^k T_s}{L} \tag{6}$$

$$i^{k+1}_L = i^k_L + \frac{V^k_{in} T_s}{L} - \frac{nV^k_{out} T_s (1-d^k)}{L} \tag{7}$$

Substituting i'_L and i^{k+1}_L in (5) leads to a quadratic equation for d^k. The acceptable answer of the quadratic equation is given in (8):

$$d^k = 1 - \sqrt{\frac{2i^k_L L + T_s V^k_{in} - 2i^k_{ref} L}{nV^k_{out} T_s}} \tag{8}$$

The input current waveform, controlled by introduced average control method is shown in Figure 5. The harmonic spectrum of the input current is shown in Figure 9. As can be seen, the value of low order harmonics have been reduced, but some kind of limit cycle oscillation observed in Figure 5. This instability in current waveform increases the ripple of the input current, especially before and after of zero crossing. This oscillations increase the high frequency harmonics, especially around half of the switching frequency. Input filter is design for switching frequency, hence these frequencies are injected into power system. In this method there is only one degree of freedom. Therefore it is not possible to control both the input current average and its ripple.

C. Two horizons prediction

As seen in the previous method, average of the input current follows reference current. But oscillation of duty cycle, increases current ripples. In the suggested method two goals for input current is defined in order to avoid limit cycle oscillation problem. These two goals of this method are as follows:

1- The average of input current over each period should trace the reference value.

2- The input current ripple should be minimized.

To achieve these two goals it is necessary to have two degrees of freedom. Therefore we use two horizons of prediction. At the first prediction horizon d^k can determine the desired i^{k+1}_L at the end of half switching cycle. Then in the second horizon both i^{k+1}_L and d^{k+1} are degrees of freedom, which can be used for achieving both goals. The input current waveform using this control strategy is shown in Figure 6. Since the minimum of ripple occurs when i^{k+1}_L and i^{k+2}_L are equal, k+1th duty cycle can be obtained from (4) as:

$$d^{k+1} = \frac{nV^{k+1}_{out} - V^{k+1}_{in}}{nV^{k+1}_{out}} \tag{9}$$

When this duty cycle is used, the input current average can be written as:

$$i^{k+1}_{ref} = i^{k+1}_{L(ave)} = \frac{i^{k+1}_L + i''_L}{2} \tag{10}$$

Where, i''_L is the peak value of current in k+1th prediction horizon. The value of i''_L can be calculated from (1) as:

$$i''_L = i^{k+1}_L + \frac{V^{k+1}_{in} d^{k+1} T_s}{L} \tag{11}$$

By substituting (9) and (11) in (10) the input current will be described as:

$$I^{k+1}_L = i^{k+1}_{ref} - \frac{(nV^{k+1}_{out} - V^{K+1}_{in}) T_s V^{k+1}_{in}}{2nLV^{k+1}_{out}} \tag{12}$$

The prediction of i^{k+1}_L from (12) and d^{k+1} from (9) guaranties both control goals in k+1th switching period. In the first switching horizon the input current should achieve the calculated i^{k+1}_L. Replacing i^{k+1}_L instead of i^{k+1}_{ref} in (4), the kth duty cycle can be derived as (13) which is used in PWM generation.

$$d^k = \frac{nV^k_{out} - V^k_{in}}{nV^k_{out}} + \frac{L(i^{k+1}_L - i^k_L)}{nT_s V^k_{out}} \tag{13}$$

Only the first calculated duty cycle (d^k) is applied to the PFC converter. At the next horizon the new values of d^k and d^{k+1} should be calculated and again first duty cycle is applied. Using this duty cycle leads to an optimized input current (related to the method goals) in the next switching cycle. The input current waveform, using suggested control method is shown in Figure 5.The harmonic spectrum of the input current is depicted in Figure 9. As can be seen, the input current harmonics have been decreased.

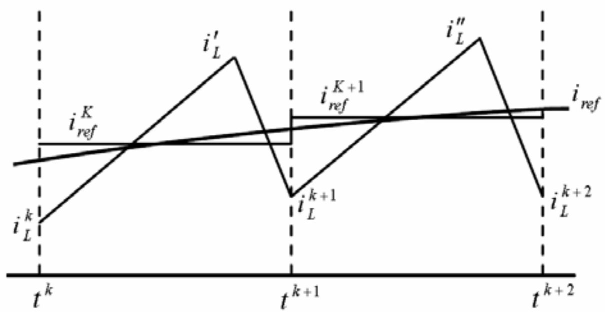

Fig. 6. The reference current and input current waveform of PFC in two prediction horizons

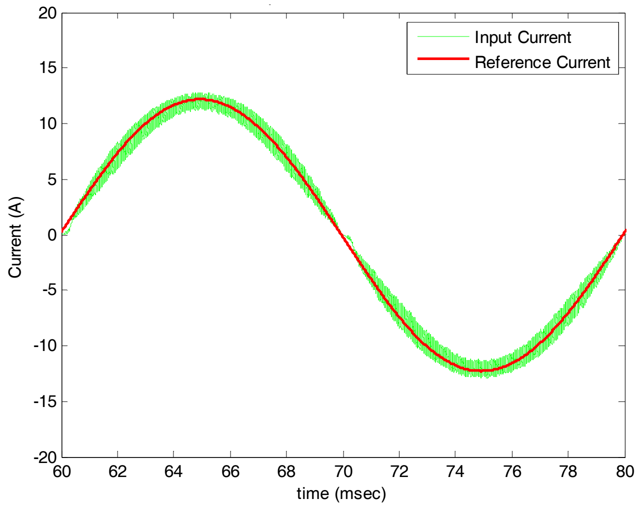

Fig. 8. The input current in suggested current control

III. EXTENDED PREDICTION

Digital controllers are realized by using a microcontrollers or digital signal processors (DSP). Digital regulators provide maximum of flexibility, but the switching frequency in the digital controllers is strongly depends on the processor speed and analog to digital converters (ADC). Different solutions have been suggested to decrease this problem. In some solutions, control method updates the duty cycles once in several switching cycles for the purpose of reducing the computation time [2]. But this method increases the injected current harmonics into the power system.

In the proposed control strategy, the A/D conversion and calculations of the new duty cycle should be terminated at the minimum shoot through time interval ($d_{\min}T_s$). Therefore in this method even at low switching frequencies, a fast digital controller should be used. Hence an extra prediction horizon is proposed to increase the computation time from ($d_{\min}T_s$) to whole switching cycle (T_s). In this method the duty cycle of each period is calculated in the previous period. The suppositional sampling and calculation time without this horizon is shown by the dash arrow in Figure 7. But using the following algorithm expands this short time interval to the whole switching period, as follows:

1- Sampling of V_{in}^{k-1}, i_L^{k-1} and V_{out}^{k-1} at the beginning of every switching period.

2- The value of output changes are negligible at a few switching period. Therefore V_{out}^{k} and V_{out}^{k+1} are approximately equal to V_{out}^{k-1}.

3- A simple linear extrapolation can be used to determine V_{in}^{k}, and V_{in}^{k+1}, using V_{in}^{k-1} and V_{in}^{k-2}.

4- The value of d^{k-1} has been calculated at previous switching period. Thus i_L^{k} can be derived using (3) as:

$$i_L^k = i_L^{k-1} + \frac{V_{in}^{k-1}T_s}{L} - \frac{nV_{out}^{k-1}T_s(1-d^k)}{L} \tag{14}$$

5- Reference current is generated from the product of input voltage (or a sinusoidal look-up table) and output of voltage controller. Therefore i_{ref}^{k+1} can be written as:

$$i_{ref}^{k+1} = V_{in}^{k+1} \times G_{PI} \tag{15}$$

6- The value of i_L^{k+1} can be obtained from equation (12).

7- The value of d^k can be calculated from equation (13).

Often, $d_{\min}$ is about 0.1, which mean the calculation time has increased 10 times using this algorithm. The current waveform using above algorithm is shown in Figure 10. As can be seen in this figure, the disturbance of input current waveform has been increase in comparison of two prediction method which is because of using simplified model. The THD of different control strategies have been presented in table II which prove the effectiveness of the algorithm.

TABLE II
THD Comparison

Control Strategy	THD (to 40th order)	Calculation time
Valley Control	4.56	$d_{\min}T_s$
Average Control	3.15	$d_{\min}T_s$
Proposed Two Horizon	1.24	$d_{\min}T_s$
Proposed Three Horizon	1.83	T_s

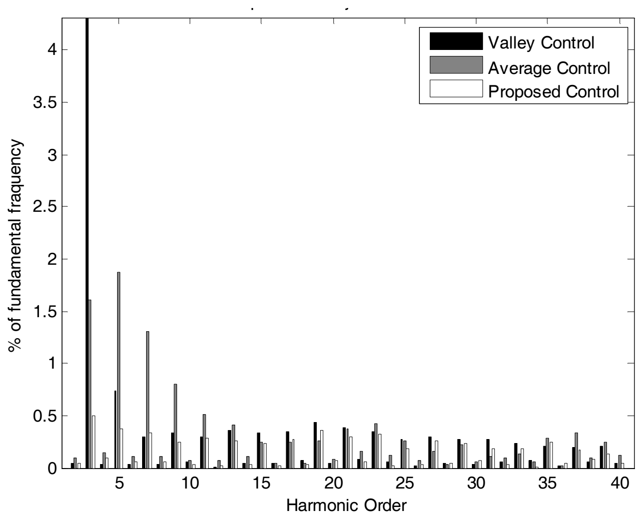

Fig. 9. Input current harmonics of PFC

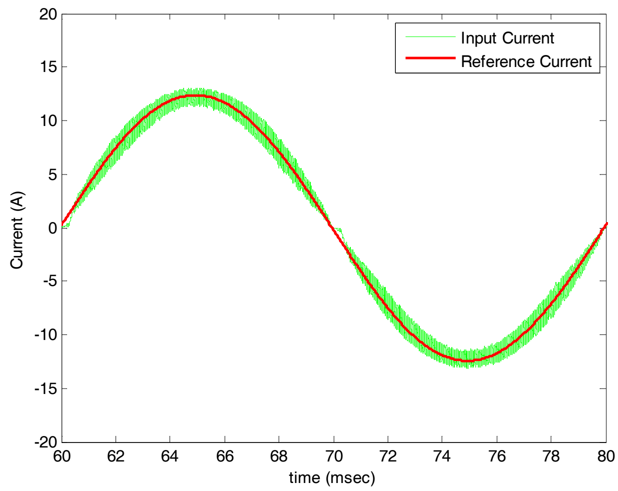

Fig. 8. The input current in three horizon control strategy

IV. CONCLUSION

In this paper, a novel predictive algorithm for input current control of isolated boost PFC has been presented. This algorithm is based on average current control method and uses two horizons of prediction. The two horizons prediction method improves the THD of input current compared of with the conventional average and valley control methods. As well, the instability in the input current waveform which causes undesirable oscillations has been eliminated. Furthermore an extra prediction horizon is proposed which extends the sampling and calculation time.

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