A New Modulation Technique for Reduced Harmonic Distortion of Current in PV Inverters

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Abstract*-This paper deals with the modeling of a single-phase PV inverter using current control. Two control methods are described; the hysteresis band and the zero-tolerance control. A study for the optimization of the Total Harmonic Distortion (THD) of the output current and for the minimization of the switching losses is being conducted. A new modulation method is also presented, defined as mixed modulation, which is a combination of the unipolar and bipolar modulation. The mixed modulation is applied both to the hysteresis band and to the zero–tolerance control. It is proved, by simulation, that this method produces the best results, since it combines the advantages of the other two modulation methods. A comparison between the modulation methods is conducted, using as criteria the THD of the output current of the inverter and the efficiency of the inverters.

***Index Terms*-- power quality, harmonic distortion, PV inverter, inverter modulation.**

I. INTRODUCTION

Photovoltaic (PV) systems require an inverter in order to connect to the grid. The modulation methods of the inverters [1-2] are a matter of continuous research and development, in order to optimize the THD of the output current and voltage and to minimize the switching losses [3-11]. The concern about these parameters is great because the THD of the current affects the harmonic distortion of the grid voltage while the inverter losses affect the energetic performance of the PV system. This paper deals with the current control of PV inverters. Two control methods are described; the hysteresis band and the zero-tolerance control. The bipolar and unipolar modulation methods are described and their operational principals are presented. The combination of these two methods has led to a new modulation method, defined as mixed modulation.

The simulation is conducted using the Psim software. Fig. 1 shows the inverter's power circuit. The nominal output power of the inverter is chosen 2.5kW. The circuit consists of a DC voltage source (V_{dc}=400V) which simulates the PV panels and the associated maximum power point tracking (MPPT) system, a full bridge inverter, a current sensor with 200 kHz sampling frequency, a low-pass filter (L=2.2mH, C=5μF) and the utility grid, which is represented by the impedance of a 630kVA, 0.4/20 kV, u_k=6% power transformer behind a sinusoidal voltage source (400 V, 50Hz). A voltage sensor samples the instantaneous voltage at the point of common coupling (PCC).

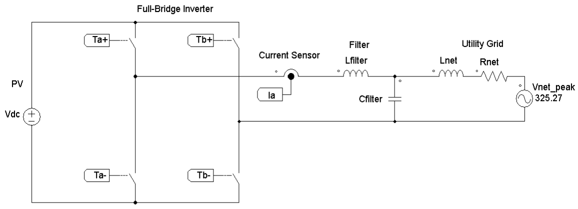

Fig 1. Power circuit of the simulated inverter.

The inverter used for the simulation is designed to keep the power factor (PF) equal to 1 at the PCC. In order to achieve this, the control circuit shown in Fig. 2 is used.

The fundamental harmonic of the output voltage is obtained through a low-pass filter and by dividing with its RMS value a new sinusoid, with unity RMS value and synchronous to the grid voltage is produced. The MPPT calculates constantly the maximum power which can be produced from the PV panels (defined as *Power Output* in Fig. 2). The power and the RMS value of the input voltage are used to obtain the desired RMS value of the inverter current (I_{an}). The instantaneous reference inverter current (I_{ref}) is obtained by the multiplication of I_{an} with the signal which is synchronous to the voltage. This control circuit manages to generate constantly the reference current from the output voltage waveform, which ensures than the current is constantly in-phase with the voltage (PF=1).

II. HYSTERESIS BAND

A hysteresis band is formed by displacing i_{ref} upwards and downwards by a percentage of its RMS value. The purpose of the controller is to maintain the current of the inverter within the limits of the band. To achieve this, the control circuit reads the value of the current at the output of the inverter. If the output current exceeds the limits of the band, the controller changes the state of the switches so that the current either drops below the upper limit or rises above the lower limit of the band. There are two main operational modes that

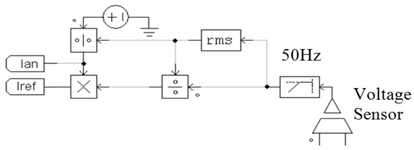

Fig 2. Control circuit used for the creation of the reference current.

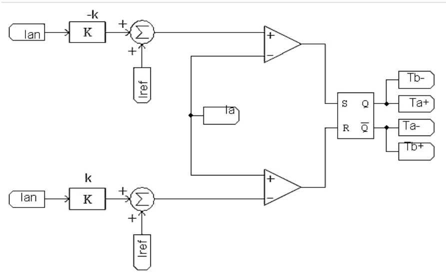

Fig. 3. Control circuit for bipolar modulation

can be used; the unipolar and the bipolar modulation. Both of them can be used with a full-bridge inverter using a different control method.

A. Bipolar modulation

In bipolar modulation the voltage at the output of the inverter can only have two values, $+V_{dc}$ or, $-V_{dc}$, where V_{dc} is the DC voltage at the input of the inverter. This operation will increase or decrease the current at the output of the inverter respectively. The control circuit used is shown in Fig. 3.

At left, the summers add a ratio (k and $-k$) of the rms value of the current to the reference current creating the upper and lower limit respectively. Then, it is compared with the actual inverter current (I_a) and the combination passes through the flip-flop which then sends the signals to the switches. The low-pass filter at the output of the inverter cuts the high-order harmonics and the filtered current waveform can be seen in Fig. 4, where it is apparent that the main distortion is located near the maximum and minimum of the sinusoidal waveform. The current distortion could be reduced by reducing the width (the k factor in Fig. 3) of the hysteresis band. This approach, however, will result in higher switching frequency which in turn will increase the inverter's losses.

Bipolar modulation has a number of disadvantages which lead to high current distortion. Near the peak of the sinusoid, when the current is rising, the voltage applied to the filter inductor is $V_{dc} - V_{net}$, where V_{net} is the network voltage which is near its maximum value as well, since the power factor is equal to 1. Thus, the current rises slowly. However, when the current passes the peak region, the voltage applied is $-V_d - V_{net}$, which has a higher absolute value, and forces the current to drop remarkably faster. This procedure creates a set of low order harmonics that are difficult to eliminate with a low pass filter. The solution is the use of unipolar modulation.

B. Unipolar modulation

With this kind of modulation, during the positive half period of the sinusoid, the switch combination applies either positive or zero voltage to the output inductor if the current should rise or drop respectively. Similarly, during the

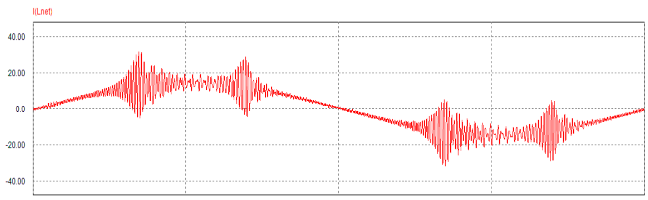

Fig. 4. Current waveform for one period (20ms) (Bipolar modulation)

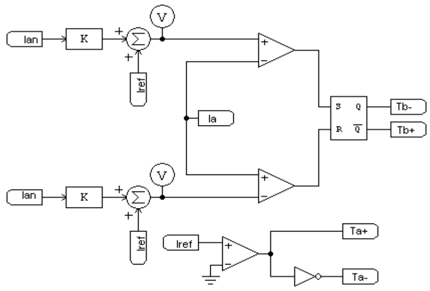

Fig. 5. Control circuit for the unipolar modulation

negative half, negative or zero voltage is applied to the output. This creates a three-level voltage at the output of the inverter. This kind of modulation is more complicated than the bipolar modulation. An additional comparator is needed to determine whether the current is located at the positive or the negative half. The control circuit can be seen in Fig. 5.

The current at the inverter output is shown in Fig. 6. It is obvious that the harmonics that appeared near the peak of the sinusoid using bipolar modulation have been eliminated; however there is high harmonic distortion near the zero crossings.

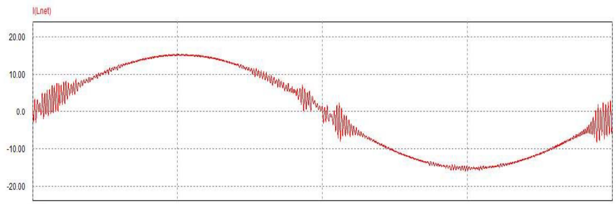

Fig. 6. Current waveform for one period (20ms) at the PCC (Unipolar modulation)

C. Mixed modulation

Summing up, bipolar modulation causes low distortion of the current near the zero crossings and high distortion near the peak value while unipolar modulation has the opposite effect. This leads to the idea of using each type of modulation where each one shows best results. This can lead to low current distortion across the entire period of the sinusoidal waveform.

In order to manage this, a 2:1 multiplexer is used, that decides which signal is lead to the switches, as shown in Fig. 7. Comparing the control circuits of each modulation type, switches T_{b-} and T_{b+} are being controlled by the same circuit, while the difference is only in the control of switches T_{a-} and T_{a+}. Specifically, either the output of the flip flop (bipolar) or the output of the comparator (unipolar) is used to control this pair. Additionally, the two switches cannot be simultaneously at the same state, so T_{a-}=NOT(T_{a+}) and vice versa.

At the lower part of Fig. 7, a comparator is used to decide the control method; it compares the absolute momentary value of the reference current with a ratio of its rms value. If the absolute value of the current is higher than the pre-defined ratio unipolar modulation is used, otherwise bipolar.

The area of unipolar modulation can change at will in order to achieve the lowest possible THD. For this reason, the Unipolar Factor is defined as the ratio of the time during

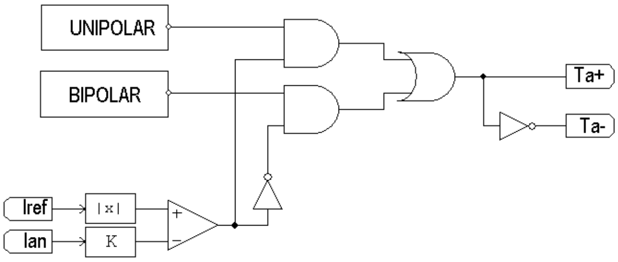

Fig. 7. Control circuit for the mixed modulation control scheme.

which unipolar modulation is used within one period. The unipolar factor is calculated by:

$$UF = 1 - \frac{1}{90} \cdot \sin^{-1}\left(\frac{k}{\sqrt{2}}\right) \tag{1}$$

where, k is the ratio used in the control circuits (Fig. 3 and 5).

To determine UF that results in the lowest THD factor, a series of simulations have been conducted, with variable UF. The results are presented in Fig. 8 where it is obvious that THD is minimized when $0.6 \leq UF \leq 0.7$. For UF=0.67, or k=0.7, simulation produces the result shown in Fig. 9 where it is clear that the majority of the high distortion has been eliminated.

III. Zero-Tolerance Modulation

This type of control is actually a sub-case of the hysteresis band control.

The width of the current band is narrowed to zero, so that there is only one reference current, and the possible states of the output current is either above or below the reference current. For this reason, the switching frequency is now controlled directly using a zero order hold (ZOH) or any other

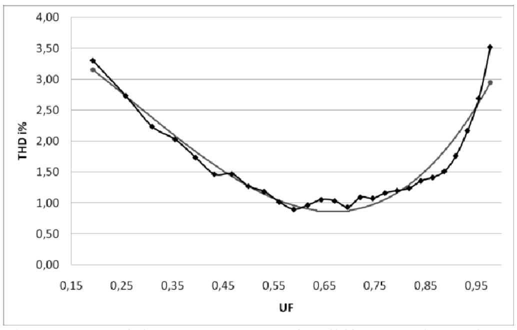

Fig. 8. THD of the output current for different values of UF.

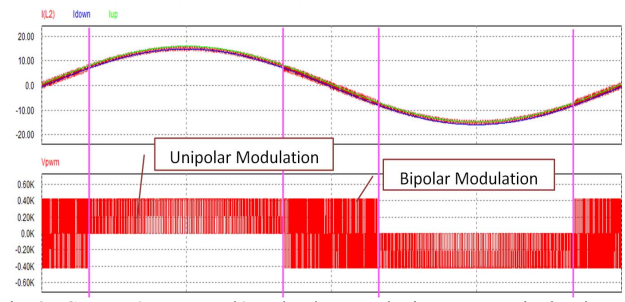

Fig. 9. Current (upper graph) and voltage at the inverter terminals when mixed modulation is used.

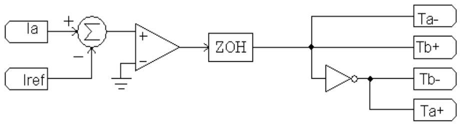

Fig 10. Control circuit used for the zero tolerance modulation

type of clocking circuit. The control circuit used for this type of modulation can be seen in Fig. 10.

The control circuit is simpler, since there is only a comparator which compares the output current with the reference current and the comparator output is sampled by a ZOH adjusted on a predefined frequency. All three types of modulation described in section II can be used with this type of control too.

IV. Comparison of the Modulation Methods

In this part a comparison between the modulation methods is conducted using as criteria the THD of the output current and the switching losses. The power circuit used for this comparison is shown in Fig.1 while the parameters are given in Table I.

TABLE I. Circuit Parameters

Nominal inverter power	2500W
V_{dc}	400V
k (Hysteresis Band)	0.005
Switching frequency (with zero-tolerance)	200 kHz
UF (mixed modulation)	0.67

For the simulation of switching losses the *thermal module* tool of the Psim software was used. The switches used for the calculation of the losses were MOSFETs (type Infineon Technologies SPA21N50C3, $V_{ds,max}$=560V, $I_{D,max}$=21A).

Fig. 11 shows a comparison of the current THD and the efficiency of the inverter for various modulation methods. It can be seen that the mixed modulation results in very low THD of the current without sacrificing the inverter efficiency.

Next an investigation was conducted regarding the influence of the DC voltage (V_{dc}) and of the band width (k) on the THD of the output current and on the switching losses when the Hysteresis Band method is used. The results are shown in Fig. 12. As expected, the reduction of the width of the band leads to reduction of the current THD and to increase of the switching losses. The increase of the input DC voltage leads in most cases to a lower current THD factor with a negative impact on the inverter's efficiency ratio.

Since in most cases the grid operator demands the current THD of the PV inverters to be less than 4%, using the mixed modulation method, the inverter's behavior is easier to optimize without a remarkable impact on the efficiency ratio and without the need of more than 450V (DC) input voltage.

Furthermore, using the mixed modulation, one can achieve the same results (concerning the current THD factor) with the bipolar or the unipolar modulation using a smaller and thus cheaper filter inductor.

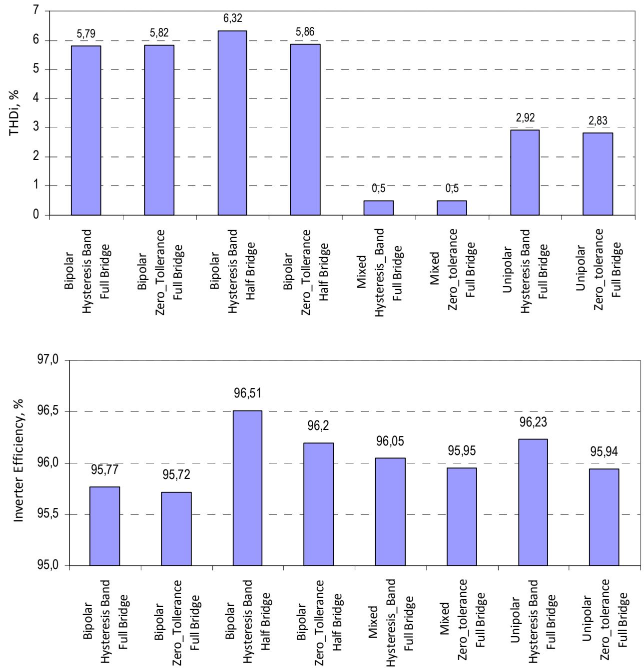

Fig. 11. THD of the output current and inverter efficiency for various modulation methods.

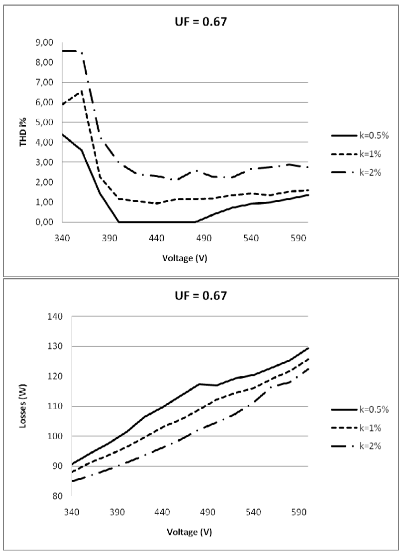

Fig. 12. Influence of the DC voltage and band width on the THD of the current and on the inverter losses

V. CONCLUSIONS

In this paper a new modulation method for single-phase current-controlled inverters that minimizes the THD of the current is presented. This method is a combination of the bipolar and unipolar modulation and is called mixed modulation. According to this method, unipolar switching is implemented for a $UF \cdot T_s$ interval within the fundamental period T_s of the current, while bipolar switching is applied for the rest $(1-UF) \cdot T_s$ interval. It is shown that the largest reduction in the THD of the current is achieved with *UF*=0.6-0.7. It is also shown that this method can maintain the inverter efficiency at high levels.

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