# HYBRID MODULATION METHOD TO REDUCE ZERO-CROSSING CURRENT OF TOTEM-POLE PFC CONVERTER

**Duc Manh Dang**
*EVSELab Co.,Ltd;*
*Hanoi University of Science and Technology*
Hanoi, Vietnam
manhdd@evselab.com

**Duc Manh Le**
*Hanoi University of Science and Technology*
Hanoi, Vietnam

**Duy Dinh Nguyen**
*Hanoi University of Science and Technology*
Hanoi, Vietnam
dinh.nguyenduy@hust.edu.vn

**ABSTRACT**

*Nowadays, Totem-pole PFC power factor correction converters are widely used in many fields, notably in electric vehicle charging stations because of their ability to transmit power in bidirectional. The principle of this converter is similar to the traditional Boost PFC topology, which does not include a bridge rectifier, so the performance is significantly improved. The lack of a bridge rectifier leads to the control of switching devices is often based on the sign of the grid voltage, this modulation method is called Unipolar. However, the input current of this converter spikes whenever the input voltage crosses zero, which is considered an inherent characteristic of this topology. To eliminate this current spike phenomenon, a new modulation method was introduced called hybrid modulation. The main point is based on switching from unipolar to bipolar modulation whenever the input voltage crosses zero, thereby eliminating the current spike. A 4kW, 220VAC, 400VDC Totem-pole PFC circuit is simulated by using PSIM 9.1 software to obviously indicate the advantages of this modulation method.*

**Keywords:** *Power factor correction, Boost PFC, Unipolar, Bipolar, Hybrid modulation, Pulse Width Modulation.*

## 1. INTRODUCTION

Power factor (PF) is defined as the ratio between active power (P) and apparent power (S). It represents the phase difference between the input current and the input voltage, along with the total input current harmonic distortion (THDi). The lower the power factor is, the larger the input current to the converter will be, leading to increased losses on the components. Therefore, maximizing the value of the power factor is extremely important, following the international standards regulating power factor such as IEC61000-3-2, Energy Star… Converters that improve power factor are called power factor correction (PFC) converters. Initially, these converters were mainly based on passive elements such as inductors and capacitors, but the power factor was not high, only about 0.8, then they were called Passive (PFC) [1]. To improve that problem, active power factor correction circuits are introduced with the advantage of a very high-power factor, which can reach approximately 1. The most common active PFC topology is Boost PFC (Fig. 3). However, when increasing the power to a few kilowatts, rectifier bridge losses constitute a significant problem for this active bridge rectifier topology [2].

Therefore, bridgeless active rectifier topologys were introduced to solve the problem of rectifier bridge losses in high-power applications, typically such as electric vehicle charging stations. Fig.4 shows the basic circuit configuration of the bridgeless PFC topology. Besides, the need for bidirectional power transmission (V2G and G2V) is increasing, so PFC topologies with this ability are introduced, especially the Totem-pole PFC topology. The circuit diagram of this topology is given in Fig. 5. This one operates similarly to a traditional Boost PFC, however, since the lack of a rectifier bridge, the control of the switching devices needs to be based on the sign of the grid voltage [3].

During the positive half cycle, device S1 acts as a Boost diode, and device S4 acts as a MOSFET Boost, along with device S2 is always ON during the entire positive cycle. Conversely, in the negative cycle, device S1 acts as a MOSFET Boost, S4 acts as a diode Boost, and device S3 is ON. This way of modulating switching devices which is based on grid voltage oil is called unipolar modulation. There are many other schemes that can be mentioned such as Bipolar, Modified Unipolar, etc. Above all, unipolar modulation is the most widely used because of its great advantages such as:

**1.1.** Best performance. Unipolar modulation requires only two high-speed switching devices, compared to four MOSFET in modulation schemes such as Modified and Bipolar. Therefore, switching losses are significantly reduced.

**1.2.** Because there are only 2 high frequency switching devices, so 2 switching devices at grid frequency can use Si devices instead of SiC. Therefore, the cost of the converter with this modulation method will be lower than the other ones.

However, this method has an inherent drawback, that is, when the input voltage passes through zero, the input current will spike which is called the Zero-Crossing current [4]. The cause of this spike current is explained in detail in [4]. Because unipolar modulation only requires two high-frequency switching devices, the low-frequency device branch often uses the Si device. Due to the slow reverse recovery characteristic of these devices, the Zero-Crossing phenomenon is created. For example, when the voltage is just changing from a negative cycle to a positive cycle, device S2 suddenly closes, device S1 immediately switches from closed with a duty cycle of 1 to 0,

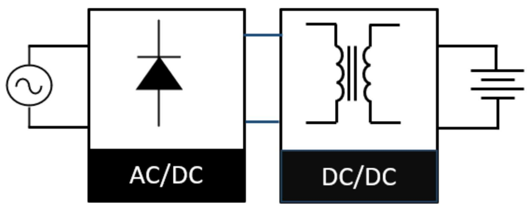


**Fig. 1.** *EV charger common topology*

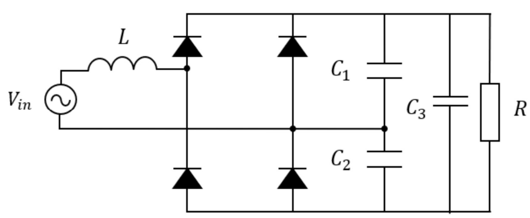


**Fig. 2.** *Passive PFC topology*

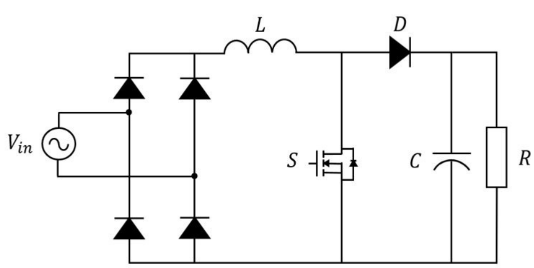


**Fig. 3.** *Traditional Boost PFC topology*

*and device S4 switches from 0 to 1.*

However, because of the slow switching characteristics of Si material, when the voltage just passes zero, device S2 is not OFF, so the voltage applied to the two poles of the inductor will be equal to Vout. Therefore, the current through the inductor spikes, which causes this current spike phenomenon, a similar phenomenon occurs at the negative half cycle.

Using Gan or Sic devices can solve this problem, but in this way the cost of converter will increase. Several solutions have been proposed, for example in [5], when the input voltage passes zero, all devices are turned off simultaneously. Therefore, the current through the inductor will not spike. However, the power factor is also affected by the current pattern when the input voltage past zero is interrupted. In [6], the author refers to a method to soft start high-frequency devices every time the input voltage passes zero, thereby reducing the zero-crossing current phenomenon. However, this option requires a complex control algorithm that needs a powerful enough microcontroller to implement. In addition, during the soft start period, there is always a device passing through the diode, leading to increased diode losses and reduced converter efficiency. Besides, a simple proposed solution is Bipolar modulation instead of Unipolar to avoid Zero spike current because when the input voltage passes zero, the duty cycle of the devices is 0.5 instead of 1 in Unipolar. However, as mentioned, this modulation method has the disadvantage of not providing high efficiency because there are 4 high frequency switching devices, and the current ripple through the inductor is 2 times higher than that of the inductor Unipolar modulation method. To take advantage of both

Unipolar and Bipolar modulation methods as well as eliminate Zero-crossing current, a new modulation method is proposed called Hybrid Modulation. In [7], the Hybrid modulation method is proposed based on the idea of Bipolar modulation whenever the input voltage passes 0, the rest of the grid cycle will be Unipolar modulation. However, the comparison of the current pulsation through the inductor as

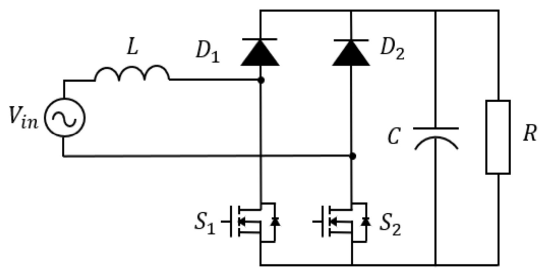


**Fig. 4.** *Bridgeless PFC topology*

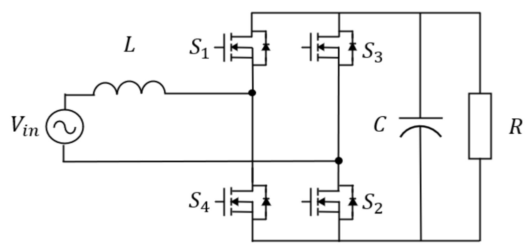


**Fig. 5.** *Totem-pole PFC topology*

well as the switching loss of the Hybrid Modulation and well modulation schemes have not been given. Therefore, this given. Therefore, this article brings forward a ripple current model, and the loss of each component as well. In Section 2, the current model through each component of the Unipolar and Bipolar modulation methods is given. Section 3 shows the modulation strategy and loss model of the Hybrid modulation method. Simulation results and analysis are given in Section 4.

## 2. UNIPOLAR AND BIPOLAR MODULATION COMPARISON

### *2.1. Unipolar modulation method*

The principle of Unipolar modulation for Totem-pole PFC topology is simply based on the sign of the grid voltage. Fig. 6 describes the modulation waveform of this alternative. In the positive half cycle which corresponds to the time t1 to t2 in Fig. 6, devices S1 is ON and S4 is OFF and device S2 is in the ON state during this entire half cycle. The voltage applied on the inductor is:

$$V_L = V_{in} \quad (1)$$

Similarly, in the period from t1 to t2, if switching S1 is OFF and S4 is in the ON state, the inductor voltage is:

$$V_L = V_{in} - V_{out} \quad (2)$$

From Equation (1) and Equation (2), the average voltage on the inductor during a switching cycle is:

$$< V_L > = V_{in} - (1 - D)V_{out} \quad (3)$$

With D = ton/T is the duty cycle of device S4, $< V_L >$ is the average voltage on the inductor during a switching cycle.

Because the average voltage of the inductor in a switching period equal zero:

$$< V_L > = 0 \quad (4)$$

Then, from Equation (4), the duty cycle of device S4 is calculated as:

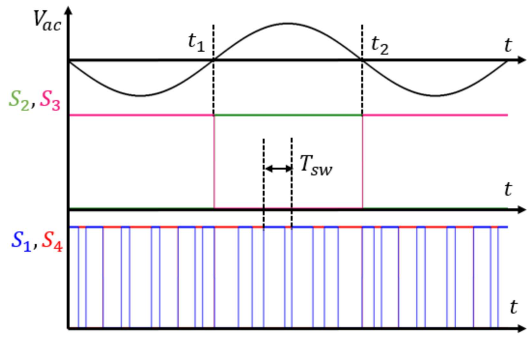


**Fig. 6.** *Unipolar modulation principle*

$$D_P = 1 - \frac{v_{in}(t)}{V_{out}} \quad (5)$$

Similarly, in the negative half cycle, the duty cycle of switch S4 is derived from equation following:

$$D_N = \frac{v_{in}(t)}{V_{out}} \quad (6)$$

During the ON state period of device S4, the current changes from the peak value to the bottom value, therefore, the value of the ripple current through the inductor is given as:

$$\Delta I_L = v_{in}(t) \times \frac{\left(V_{out} - v_{in}(t)\right)}{V_{out} \times f_{sw} \times L} \quad (7)$$

With L is the inductance value of the grid-side inductor, $v_{in}(t)$ is the instantaneous value of the input voltage, $V_{out}$ is the output voltage value, $f_{sw}$ is the switching frequency of the high-frequency device branch.

The maximum ripple current value is obtained by taking the time derivative of the instantaneous ripple current value, the result is given in Equation:

$$\Delta I_{Lmax} = \frac{V_{out}}{4 \times f_{sw} \times L} \quad (8)$$

From Equations (7), the root mean square of ripple current is:

$$\Delta I_{L,rms} = \sqrt{\frac{1}{\pi} * \frac{V_{in}^2}{f^2 L^2} * \left(\left(\frac{1}{2} + \frac{3V_{in}^2}{8V_o^2}\right)\pi - \frac{8V_{in}}{3V_o}\right)} \quad (9)$$

From Equation (9), the root mean square (RMS) value of the inductor current is:

$$I_{L,rms} = \sqrt{(i_{in} * \sin(\omega t))^2 + \frac{\Delta I_{L,rms}^2}{12}} \quad (10)$$

From Equations (9) and (10), the root mean square current through the inductor of the Unipolar modulation method is:

$$I_{Q,rms} = I_{L,rms} * \sqrt{D} \quad (11)$$

### *2.2. Bipolar modulation method*

Unlike the Unipolar modulation method, the Bipolar modulation method is completely independent of the sign of the input voltage. The principle of operation of the converter with this modulation method is given in Fig. 7.

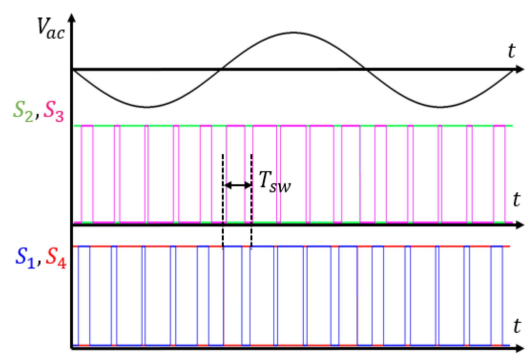


**Fig. 7.** *Bipolar modulation principle*

S1 and S2 are in the ON state at the same time, the voltage across the inductor is:

$$V_L = V_{in} - V_{out} \quad (12)$$

On the contrary, when devices S3 and S4 are in the ON state at the same time, the voltage value on the inductor is:

$$V_L = V_{in} + V_{out} \quad (13)$$

From Equation (12) and Equation (13), the average voltage on the inductor during a switching cycle is:

$$< V_L > = V_{in} + (1 - 2D)V_{out} \quad (14)$$

The instantaneous ripple current value through the inductor is:

$$\Delta i_L(t) = \frac{V_{out}^2 - v_{in}(t)^2}{2 \times V_{out} \times f_{sw} \times L} \quad (15)$$

The maximum value of the ripple current is given as follows:

$$\Delta I_{Lmax} = \frac{V_{out}}{2 \times f_{sw} \times L} \quad (16)$$

From Equation (15), the root mean square (RMS) value of the ripple current is:

$$\Delta I_{L,rms} = \sqrt{\frac{1}{\pi} * \frac{1}{4f^2L^2} * (\frac{3\pi V_{in}^4}{8V_o^2} - V_{in}^2\pi +} \quad (17)$$

Similarly, the root mean square current through the MOSFET is given as follows:

$$I_{Q,rms} = I_{L,rms} * \sqrt{D} \quad (18)$$

It can be seen that, compared to the Unipolar modulation method, the Bipolar modulation method gives a higher ripple current value, which leads to a low power factor. Greater RMS current through the inductor and through the device results in lower efficiency. The advantages and disadvantages of these two modulation options are summarized in Table 1.

**TABLE 1.** *Comparison of modulation methods*

| Modulation method | Advantages | Drawbacks |
|---|---|---|
| Unipolar | High efficiency<br>Low cost | Zero Crossing current |
| Bipolar | Non-Zero Crossing current | Low efficiency<br>High EMI noise |

## 3. HYBRID MODULATION STRATEGY

As shown in Table 1, Bipolar modulation helps to eliminate the problem of Zero-crossing current, Unipolar modulation brings the higher efficiency and power factor out in the other regions. Therefore, the Hybrid modulation method takes advantage of both the above modulation methods.

The Hybrid modulation principle, described in Fig. 8, when the input voltage is about to reach 0 value and change sign, Bipolar modulation method will be applied. Conversely, when the output voltage is over the Zero-Crossing region, Unipolar modulation is back applied.

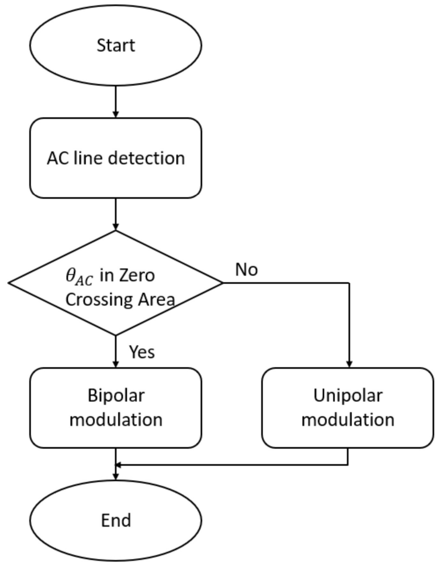


**Fig. 8.** *Hybrid modulation strategy*

RMS of ripple current value through the induction coil with Hybrid modulation method:

$$\Delta i_{L,rms}^2 = \frac{1}{\pi - 2\alpha} * \frac{V_{in}^2}{f^2L^2} * (\left(\frac{1}{2} + \frac{3V_{in}^2}{8V_o^2}\right)(\pi - 2\alpha) + \left(\frac{1}{2} + \frac{V_{in}^2}{2V_o^2}\right) sin(2\alpha) - \frac{V_{in}^2}{16V_o^2} sin(4\alpha) + \frac{V_{in}}{3V_o} cos(3\alpha) - \frac{3V_{in}}{V_o} cos(\alpha)) + \frac{2}{\alpha f^2 L^2}\left(\frac{3V_{in}^4}{8V_o^2} - V_{in}^2 + V_o^2\right) \quad (19)$$

Likewise, the RMS current through the device is:

$$i_{Q,rms} = I_{L,rms} * \sqrt{D} \quad (20)$$

From Equation (10) and Equation (20), compared to the Unipolar modulation method, Hybrid modulation has an additional switching loss whenever a Zero-Crossing event occurs. However, according to Equation (19) the increasing in RMS current through the inductor is insignificant. So, in general, the efficiency of converter with Hybrid modulation and traditional Unipolar method is almost the same. The simulation results will be presented in detail in Section 4.

## 4. SIMULATION RESULTS

To verify the hybrid modulation method, a Totem-pole PFC 4kW, which has an input voltage of 85VAC to 240VAC, and an output voltage of 400VDC, is simulated on PSIM 9.1 software. The value of inductance L is 350μH, the output capacitor is 1mF, and the switching frequency is chosen to be 65kHz. Along with that, the circuit performance is also calculated to compare the performance between modulation methods. The two quick bypass devices used are SiC UJ4C075023K3S from United SiC. The two slow device branches used are IPA60R060P7 from Infineon.

### *4.1. Simulation verifies the input current waveform*

Fig. 9 and Fig. 10 describe the simulation results of the input current waveform of each modulation method. It can be seen that, in the traditional Unipolar method when the input voltage passes the zero value, the current spikes very large, reaching 20A. Therefore, the power factor is greatly reduced. In Fig. 11, the input current waveform of the Hybrid modulation method is given: the ripple current is increased when input voltage crosses zero value because of characteristic of Bipolar modulation. However, it is still much lower compared to Unipolar modulation.

In Fig. 12 and Fig. 13 the Hybrid modulation method gives the highest power factor, which proves that this modulation method is effective in improving the maximum power factor by 0.999 and 0.995 in high line and low line cases, respectively. This proves that the Hybrid modulation is effective in Power Factor improvement.

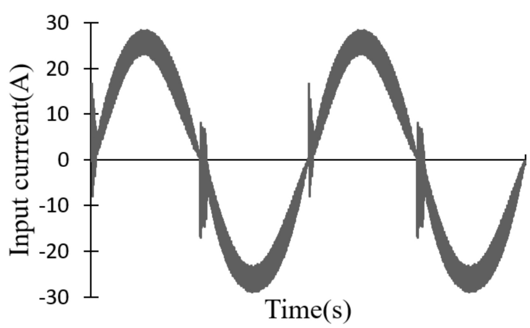


**Fig. 9.** *Input current wave form of Unipolar modulation method*

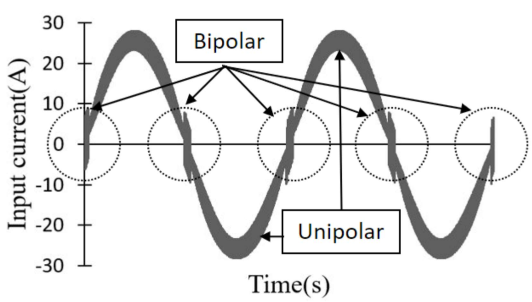


**Fig. 10.** *Input current wave form of Hybrid modulation method*

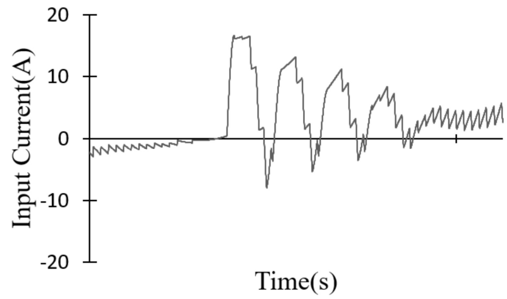


**Fig. 11.** *Zero crossing current wave form of Unipolar modulation method*

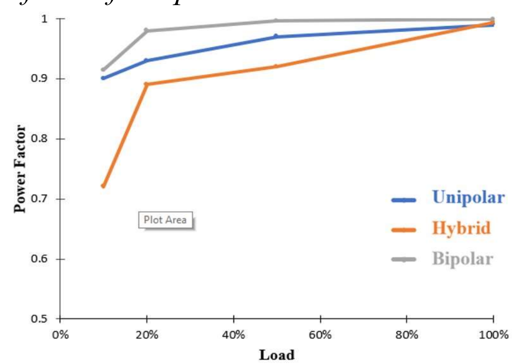


**Fig. 12.** *Power factor curve of modulation methods at low line (110VAC)*

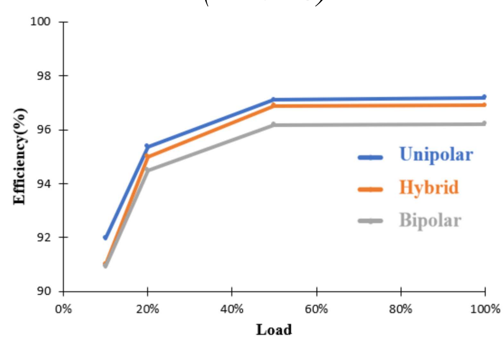


**Fig. 13.** *Efficiency of modulation methods at low line (110VAC)*

### *4.2. Performance of modulation methods*

Fig. 15 and Fig. 16 show the converter performance in the high-line and low-line cases for all three modulation methods. In high-line conditions, the performance of Unipol--ar and Hybrid are likely no different, the Bipolar modulation scheme gives about 0.5% less efficiency methods. In high-line conditions, the performance of Unipolar and Hybrid are likely no different, the Bipolar modulation scheme gives about 0.5% less efficiency. The low line that is shown in Fig. 15, Unipolar's efficiency is the highest, reaching a maximum value of 97.8% at 50% load. Unipolar and Bipolar modulation methods give peak efficiencies are 97.5% and 96.2% respectively.

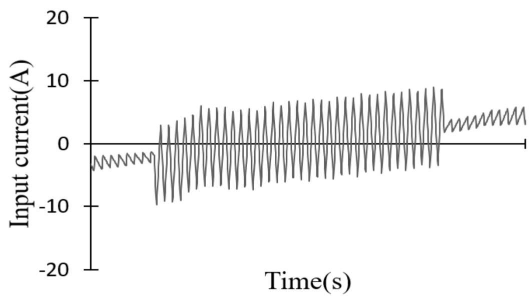


**Fig. 14.** *Zero-Crossing current wave form of Hybrid modulation method*

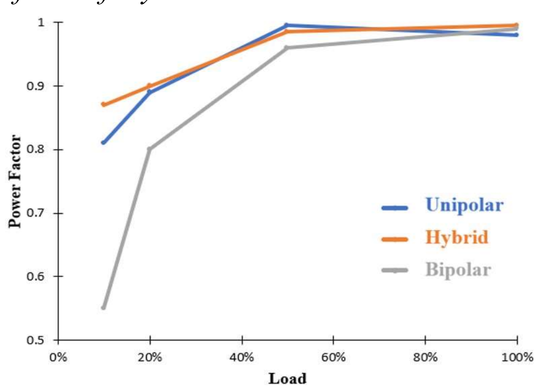


**Fig. 15.** *Power factor curve of modulation methods at high line (220VAC)*

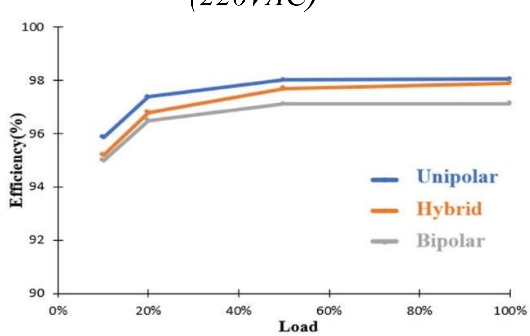


**Fig. 16.** *Efficiency of modulation methods at high line (220VAC)*

## CONCLUSION

The hybrid Modulation method is introduced to eliminate the current spike when the input voltage crosses 0 for the Totem- pole PFC topology. The principle of this modulation method is simple: when the input voltage is in the Zero Crossing area, Bipolar modulation is performed, and in the remaining areas, Unipolar modulation is performed. From there, the advantages of both of the modulation methods are taken advantage of and Zero Crossing current is also eliminated. The equations for the ripple current through the inductor and the effective current through the device of all three modulation methods are given for comparison. The Hybrid modulation method gives the best efficiency in terms of power factor which is insignificantly smaller than Unipolar modulation and greater than Bipolar. Totem-pole PFC 4kW simulation system that has an input voltage of 85VAC to 240VAC, an output voltage of 400VDC, simulated on PSIM 9.1 software was built to verify the calculation results. Simulation results indicate that the Hybrid modulation method can eliminate Zero Crossing currents, thereby improving the power factor. Additionally, the controller's response is not affected. Therefore, this is a potential preparation method, which tends to become a commonly used method in industry.

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