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Performance of difference PFC converter for improved converter efficiency: A Review

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Abstract

In this paper, Different bridgeless single-phase ac–dc converters with an automatic power factor correction (PFC) is studied, and compare new proposed “A Three-Level Quasi-Two-Stage Three-Phase PFC Converter” with all PFC converters. The proposed PFC converter features sinusoidal input current, three-level output characteristic, and a wide range of output DC voltages, and it will be very suitable for high power applications where the output voltage can be either lower or higher than the peak AC input voltage, e.g. plug-in hybrid electric vehicle (PHEV) charging systems.

Moreover, the involved DC/DC buck conversion stage may only need to process partial input power rather than full scale of the input power, and therefore the system overall efficiency can be much improved. Through proper control of the buck converter, it is also possible to mitigate the double-line frequency ripple power that is inherent in a single-phase AC/DC system, and the resulting load end voltage will be fairly constant. The dynamic response of this regulation loop is also very fast and the system is therefore insensitive to external disturbances.

Keywords: AC/DC converter, active power decoupling, conduction losses, current regulation, electric vehicle charger, power factor correction, harmonic distortion

1. Introduction

With the ever increasing use of power electronic equipment, employing rectifiers is unavoidable in many applications. The major problem with the conventional rectifiers is harmonic pollution [1]. Today’s standards like International Electro technical Commission (IEC) 61000-3-2 limit the harmonics produced by these devices [2]. Therefore, to satisfy the standards, power-factor-correction (PFC) converters are used for ac–dc conversion. The conventional PFC converter is a boost converter, and thus, the output voltage must be greater than the input voltage [3]. In spite of this problem, this converter is widely used because of its simplicity.

In large number of applications, like offline low-voltage power supplies, where it is preferred to have the PFC output voltage lower than the input ac voltage, a buck-type converter is required. However, the input current of buck converter is discontinuous, and to filter this current, another passive filter must be used at the buck converter input. Presently, Three-phase power factor correction (PFC) converters are a very popular solution to ensure the compliance of such regulations because of their simplicity, cost effectiveness and good current shaping capability. However, most of the existing Three-phase PFC converters are of boost type and can only provide an output voltage that is higher than the peak voltage of the AC input [4]. Wide range of output voltage is indeed desired in some applications like in plug-in hybrid electric vehicle (PHEV) charging systems where the terminal voltage of battery packs may vary between 100V to 600V

In order to provide flexible DC output voltages, PFC converters with buck-boost capabilities have been studied in the literatures and they are usually based on buck-boost, flyback, Cuk, and Single-ended primary inductance converter (SEPIC) topologies, and can be derived in both non-isolated and isolated versions [5]. A common problem for these topologies is that there is no direct energy transfer path during power conversion and all input power must be processed by active switches and stored by intermediate passive components (either inductors or capacitors) before being supplied to the end loads [6].

2. Power Factor & THD for AC/DC Converter

The distortion of the normal sine wave by non-linear loads is created by harmonics. Harmonics are related to the fundamental frequency and are defined as whole number multiples of the fundamental frequency. THD of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of all harmonic components of the voltage or current waveform compared against the fundamental component of the voltage or current wave.

$$THD = \frac{\sqrt{{I_2}^2 + {I_3}^2 + --- + I_N^2}}{I_1} = \frac{\sqrt{\sum_{N=2}^{N} {I_N}^2}}{I_1} \qquad (1)$$

Where I_N is the magnitude of N^{th} order harmonic component of current.

Power factor is a measurement of how efficiently a facility uses the electrical energy and is given as:

$$PF = Distortion_{pf} \times Displacement_{pf} \qquad (2)$$

Where

$$Displacement_{pf} = \cos \emptyset \qquad (3)$$

Non-linear loads have large values of THD, and cause considerable distortion to the normal sine wave. The more the sine wave gets distorted, the lower the total power factor becomes. Usually, total power factor is associated only with the phase displacement of the voltage waveform to the current waveform, but harmonics also affect the total power factor.

Harmonic problems are generally caused by non linear loads such as adjustable speed drives, arcing devices, electronic ballast and switching power supplies. They can cause the nearby equipments to malfunction, voltage distortion and trigger a resonance with the utility. The relation between distortion power factor and THD is given by:

$$Distortion_{pf} = \sqrt{\frac{1}{1+THD^2}} \qquad (4)$$

Distortion power factor takes into account the harmonic currents that do not contribute to the real work produced by the load where as displacement power factor relates to the displacement between the system current and voltage waveform. Based on these two parameters the following AC/DC converters are analyzed.

2.1 Three phase diode rectifiers

A six-pulse uncontrolled diode rectifier with a dc load R_L is shown in Fig 1.Three phase diode rectifiers are often used in Industry to provide the dc input voltage for motor drives and dc-to-dc converters [7]. These rectifiers are extremely robust and present low cost, but draw non-sinusoidal currents or reactive power from the source, deteriorating the electrical power system quality [8].

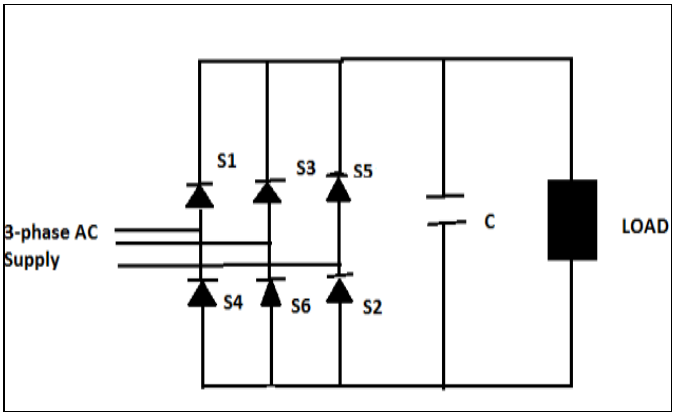

Fig 1: Six-pulse uncontrolled diode rectifier

It is seen that the fundamental component of current is in phase with the supply voltage and hence the displacement power factor is unity. Harmonic currents present in supply current consist of 3,5,7,9 …..Order of harmonics with Magnitude $\frac{I_3}{3}, \frac{I_5}{5}, \frac{I_7}{7}$ ……… Hence the distortion power factor will be low which results in poor power factor. The harmonic current injections affect the power system by distorting the bus voltage at the point of common coupling. These aspects have a negative influence on both power factor and power quality. The current THD for diode rectifiers is usually high at 30% and the power factor is 0.954 [10]. It is seen that although the displacement power factor is unity, the distortion power factor is high due to large harmonic content resulting in low power factor. Hence if we use diode rectifiers for high power application, filters are to be used to improve power factor so as to make input current a sinusoidal one.

2.2 Three -phase controlled rectifier

The thyristor valves are used for conversion of AC into a controlled DC and thus are the central component of any HVDC converter station. They are also used in various classes of railway rolling systems so that fine control of the traction motors can be achieved. A phase controlled rectifier is accomplished by replacing the diodes in a 6- pulse rectifier with thyristors. Since a thyristor needs a triggering pulse for transition from nonconducting to conducting state, the phase angle at which the thyristor starts to conduct can be delayed. A six pulse controlled rectifier using thyristor is shown in Fig. 2 With firing angle $\cos\alpha = 0$, the input current waveform for controlled and uncontrolled rectifier will be the same. As α is increased, distortion in the current waveform also increases. As it is known that displacement power factor for thyristor rectifier will be $\cos\alpha$ hence total power factor will be low. As seen in three phase diode rectifier, harmonic currents present in supply current consist of 3,5,7,9 ….. Order of harmonics.

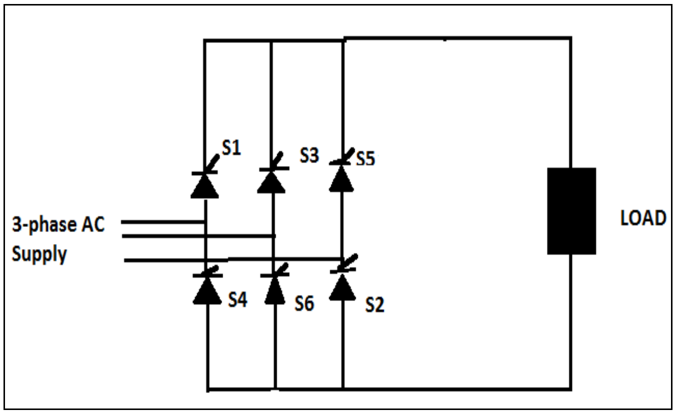

Fig 2: Six-pulse controlled bridge rectifier

Hence the distortion power factor will be high which results in poor power factor. The poor power factor causes high apparent current and the absolute harmonic currents are higher than those with a diode rectifier. Hence, in the case of controlled rectifiers, both capacitor banks and passive filters are required to make the input current nearly sinusoidal.

3. Literature Review

3.1 Different PFC converters to improve efficiency & less conduction losses

1. Bridgeless PFC boost rectifiers

The bridgeless PFC boost rectifiers, also called the dual boost PFC rectifiers, compared to the conventional PFC boost rectifier, generally, improve the efficiency of the front-end PFC stage by eliminating one diode forward-voltage drop in the line-current path. The basic bridgeless PFC boost rectifier is not a practical solution because it has significantly larger common-mode noise than the conventional PFC boost rectifier. Today, two topologies can be considered as attractive for practical implementation: the bridgeless PFC boost rectifier with the bidirectional switch [9] and the bridgeless PFC boost rectifier with two dc/dc boost circuits.

The CCM bridgeless PFC boost rectifier had an improved efficiency of 1-2% at output power levels 350-750 W and around 3.5% at 20% load, whereas, the DCM/CCM boundary bridgeless PFC boost rectifier improved the efficiency by 0.8% at full load and by almost 5% at 20% load at worst case compared to their respective conventional CCM and DCM.

2. Interleaved boost PFC

In this point, a new interleaved boost PFC converter is proposed, which provides soft switching for the power MOSFETs, through an auxiliary circuit. This auxiliary circuit provides reactive current during the transition times of the MOSFETs to charge and discharge the output capacitors of the MOSFETs. In addition, the control system effectively optimizes the amount of reactive current required to achieve ZVS for the power MOSFETs. The frequency loop, which is introduced in the control system, determines the frequency of the modulator based on the load condition and the duty cycle of the converter.

The proposed converter shows better efficiency for the whole load range compared to the conventional one. The improvement in the efficiency can be attributed to the fact that the proposed converter eliminates two main sources of losses, which are the turn-ON losses of the boost MOSFETs and the reverse-recovery losses of the output diodes.

3. Single-stage high PF electronic ballast with ZVS Buck–Boost Conversion

In this type single-stage high-power-factor electronic ballast has been presented. The circuit topology is based on the integration of a half-bridge resonant inverter for ballasting the fluorescent lamp and a derivative buck–boost converter for PFC. The elaborate design on circuit parameters ensures that both the active power switches can achieve ZVS features, leading to a high efficiency. A prototype circuit designed for a T8-36W fluorescent lamp is built and measured to verify the theoretical analyses. Experimental results show that the ballast-lamp circuit performs satisfactorily from preheating through ignition to the steady state. Under the nominal operation conditions, a nearly unity power factor and a THD of less than 9% can be achieved. With ZVS operation on both active power switches, the electronic ballast has a high circuit efficiency of 0.94.

4. Flyback Topology

The flyback topology is suitable for achieving power factor correction. Isolation and bus voltage regulation using only one power conversion step. In addition, the active switch is in series with the input, allowing simple inrush current limiting and over current protection. As *a* result, the flyback configuration is an attractive alternative to the conventional two-stage scheme typically used in power distribution system. For PFC applications, the active clamp flyback offers essentially the same advantages as for dc/dc conversion applications. The method of charge control can be applied for CCM operation, reducing component current stress and increasing power processing capabilities. A drawback to the use of the flyback is the relatively high voltage and current stress suffered by its switching components.

5. Single-Stage Isolated Power-Factor Corrector

In this converter, we introduced a new family of single-stage isolated power-factor-corrected power supplies (S^2PI^2’). The family members feature fast regulation of the output voltage, one or two power switches controlled in unison, a single FWM control loop, and automatic shaping of the line current. When the inductors *of* the (S^2PI^2’) circuits operate in DCM (the preferred operating mode), the voltage of the storage capacitor becomes independent from the load. The (S^2PI^2’) family represents a low-cost alternative to the traditional two-stage PFC power supplies and is free from the disadvantages *of* other single stage circuits.

6. Boost-interleaved buck-boost (BoIBB) converter

A new two-switch topology, named boost-interleaved buck-boost (BoIBB) converter, is proposed for universal-input PFC applications. A comparison with conventional buck-boost or two-switch buck-boost converters shows that the BoIBB converter has advantages of lower switch voltage stresses, potentials for lower switch and inductor conduction losses, and reduced size of the magnetic.

7. Bridgeless SEPIC PFC Rectifier

In this topology the absence of an input diode bridge and the presence of only two semiconductor switches in the current flowing path during each switching cycle results in less conduction losses and improved thermal management compared to the conventional SEPIC PFC converters [10]. In this converter, a new bridgeless SEPIC PFC rectifier has been introduced. The proposed circuit provides lower conduction losses with reduced components simultaneously. Two diodes of input rectifier are substituted with two switches in order to use one switch for SEPIC converter. In conventional PFC converters (CCM boost converter), a voltage loop and a current loop are needed for PFC. By using DCM operation in the proposed converter, the control circuit is simplified, and the current loop is omitted. The main features of the proposed converters include high efficiency, low voltage stress on the semiconductor devices, and simplicity of design. These advantages are desirable features for low-voltage power-supply applications. The measured efficiency shows 1% improvement in comparison to conventional bridgeless SEPIC rectifier.

8. Bridgeless Cuk Rectifiers for PFC Applications

The absence of an input diode bridge and the presence of only two semiconductor switches in the current flowing path during each interval of the switching cycle result in less conduction losses and an improved thermal management compared to the conventional Cuk PFC rectifier [11]. The proposed topologies are designed to work in discontinuous conduction mode (DCM) to achieve almost a unity power factor and low total harmonic distortion of the input current. The DCM operation gives additional advantages such as zero-current turn-ON in the power switches, zero-current turn-OFF in the output diode, and simple control circuitry. In this Bridgeless topologies can improve the efficiency by approximately 1.4% compared to the conventional PFC Cuk rectifier.

9. SWISS Rectifier (SR)

This topology deals with a three-phase unity power factor buck type PFC rectifier, named the SR [12], appropriate not only for high power EV battery charging systems, but also for power supplies for telecommunication, future more electric aircraft, variable speed ac drives, and high-power lighting systems. The complete design procedure of this system is based on analytical expressions of the current stresses of the active and passive power components, including a simplified EMI DM/CM modeling for conducted emission and filter design. Additionally, a 7.5 kW SR hardware prototype has been implemented and its feasibility has been verified. The SR is a very suitable topology for the implementation of a buck-type PFC mains interface for an EV battery charger.

10. Zero-Voltage-Switching Control for a PWM Buck Converter

In this converter, an integrated ZVS control technique has been presented for PWM buck converters under DCM/CCM boundary. Commercial control chips with similar ZVS functions either require additional external components and timing calculation circuits or depend on precise user-defined parameter specifications to assist ZVS. The presented control scheme automatically determines and compensates for the circuit delay. Also, it achieves ZVS without any additional external components or timing calculation circuits. The experimental results illustrate the effectiveness of the proposed ZVS control scheme. At 3.6 MHz, the measured conversion efficiency with the presented ZVS technique is 11% higher than that without ZVS.

11. Variable On-Time (VOT) -Controlled Critical Conduction Mode Buck PFC Converter

This topology presents a variable on-time control method to reduce individual harmonics for a CRM buck PFC front-end converter in lighting applications. Based on the conventional COT control circuit, a modulation index with simple implementation is introduced into the control circuit. It is used to achieve low THD and meet the IEC61000-3-2 Class C limitations. With the optimized control parameters, both high efficiency and high power factor are achieved. Furthermore, with the low bus voltage, the voltage stresses of the bus capacitor and downstream stage are depressed. Hence, low-voltage and low-cost electrolytic capacitors with long lifetime can be utilized. The cost of dc/dc stage can be reduced too. A two-stage prototype including the buck PFC front-end and a dc/dc as the second stage verifies the theoretical analysis. The measured line current harmonics meet the IEC 61000-3-2 Class C limits and the efficiency of buck PFC stage exceeds 96% in whole input voltage range.

4. Problem Solution with New Invention

4.1 Three level two stage three phase PFC converter.

After deeply studying above papers & finding with different problems, we search out solutions with different techniques on "Converter" This topology presents a three-level quasi-two-stage three-phase power factor correction (PFC) converter that has flexible output voltage and improved conversion efficiency. The proposed PFC converter features sinusoidal input current, three-level output characteristic, and a wide range of output DC voltages, and it will be very suitable for high power applications where the output voltage can be either lower or higher than the peak AC input voltage, e.g. plug-in hybrid electric vehicle (PHEV) charging systems. Moreover, the involved DC/DC buck conversion stage may only need to process partial input power rather than full scale of the input power, and therefore the system overall efficiency can be much improved. Through proper control of the buck converter, it is also possible to mitigate the double-line frequency ripple power that is inherent in a single-phase AC/DC system, and the resulting load end voltage will be fairly constant. The dynamic response of this regulation loop is also very fast and the system is therefore insensitive to external disturbances.

The circuit diagram of the proposed three-phase AC/DC converter is shown in Fig. 3, which consists of a standard diode rectifier bridge, a three-level PFC, and a bidirectional DC/DC converter. The PFC stage are connected with two DC buses, i.e. a low voltage DC bus that directly supplies power to the load, and a high voltage DC bus that supports three-level operation and absorbs system harmonic power. The two buses are interconnected with each other through the bidirectional DC/DC converter, and the high voltage DC bus may also serve as the dc-link of a three-phase inverter that is usually used to drive the load. It should be noted that bidirectional operation of the proposed topology is also possible at the expense of increased number of gate drivers, e.g., the diode rectifier bridge should be replaced by an unfolding bridge, and D1 and D2 should be replaced by MOSFETs with anti-parallel diodes.

As mentioned above, the proposed three-level PFC has a wide range of output voltages and it can function as either a buck or a boost converter.

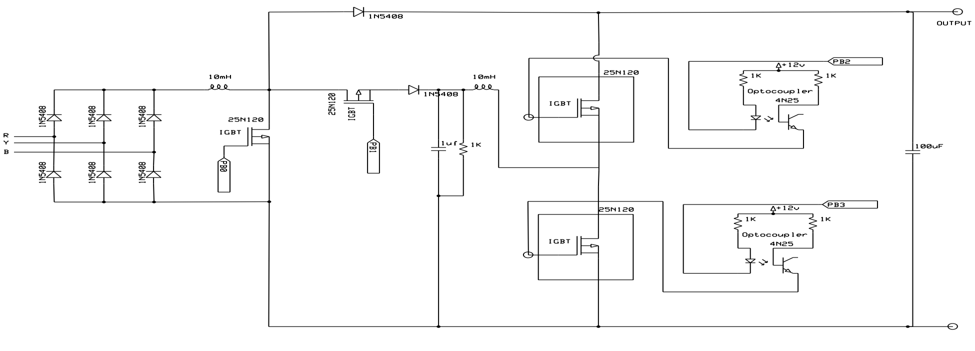

Fig 3: Circuit diagram of the proposed three-level PFC converter for three-phase.

4.2 System Controller Design.

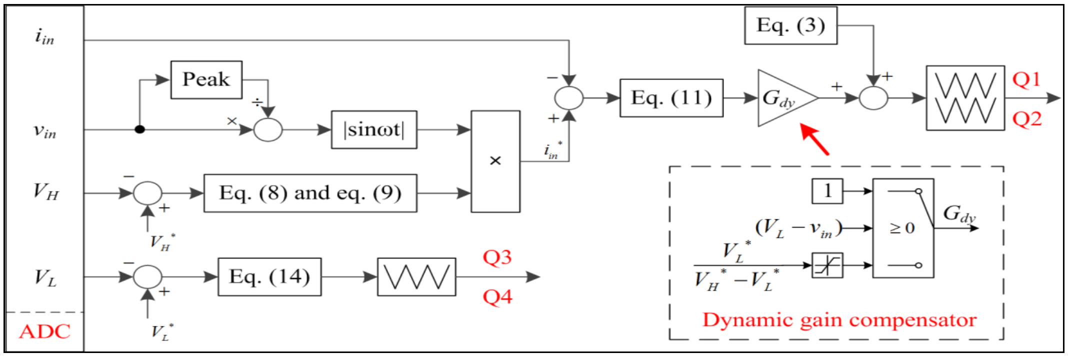

Fig 4: Overall control block diagram for the proposed three-level PFC converter.

A classic cascaded control structure is employed to regulate the PFC converter. Its outer voltage control loop is tasked at balancing input and output power, and the dc-link voltage V_H is chosen as the control variable because the charging power into the dc-link capacitor C_H is directly proportional to input power as long as V_L, V_{in}, and V_H are fixed. This voltage control loop will also maintain the average value of V_H to be constant, whereas its instantaneous value is not necessary to be constant, because the dc-link capacitor C_H has to absorb the double line frequency harmonic in this single-phase system. The control loop is therefore of slow response and its control bandwidth is set below 20Hz as per usual design, and this is realized by tuning the parameters of a proportional-integral (PI) regulator. *Vdc* is the output voltage that may change between V_L and (V_H-V_L), depending on the operation mode of the PFC.

It is worth noting that this voltage change is undesired in the system, because it may give rise to a variable bandwidth of the current control loop and affect its regulation performance. In order to have a fixed control bandwidth for the inner current loop, a dynamic gain compensator is implemented as shown in the right bottom part of Fig. 4, and an upper saturation is set to limit the gain value. In this case, the inner current loop can be easily controlled by another PI regulator. In order to achieve accurate current tracking and make the control system robust against line voltage change, a duty cycle feed-forward control scheme is also implemented in the current loop.

5. Application

1. It has flexible output voltage and can be used for single-phase PHEV charger applications, where the battery voltage can be either lower or higher than the peak AC input voltage.
2. Used to reduce conduction losses.
3. Used in industries which have low power factor problems.
4. It is also used for low-output voltage applications, such as telecommunication or computer industry.
5. Used to improve Power factor & reduce total harmonic distortion.

6. Conclusion

In this paper, Different PFC converter has been studied & a three-level quasi two-stage three phases PFC is presented. It has flexible output voltage and can be used for single-phase PHEV charger applications, where the battery voltage can be either lower or higher than the peak AC input voltage. The proposed converter features high quality input current, three-level output voltage, and improved conversion efficiency. By designing a fast regulation loop for the buck converter, the inherent fluctuating power issue in single phase systems can also be resolved, and the load voltage will be fairly constant and insensitive to load changes and external disturbances. Moreover, a dynamic gain compensator is implemented in the current control loop and in this case, its control bandwidth can be kept relatively constant irrespective of the DC bus voltage change during two different operation modes. Therefore, the grid current can be well regulated with low THD and high power factor.

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