ANALYSIS AND SIMULATION OF THREE PHASE DIODE RECTIFIER WITH A NOVEL UNITY POWER FACTOR INPUT STAGE USING HYBRID UNIDIRECTIONAL RECTIFIER

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Abstract

In this paper, a method of improving the input current total harmonics distortion (THD) as well as power factor of three phase diode rectifier is implemented. In this method, a single-switch diode bridge boost-type rectifier in parallel with a pulse width modulation (PWM) three-phase unidirectional boost rectifier are used across the three-phase supply and load. The objective is to obtain a structure capable of providing sinusoidal input currents with low harmonic distortion and dc output voltage regulation. The operation of the converter is fully analyzed and simulation is also presented in this paper.

Key words: High-power application, hybrid rectifier, power factor improvement, pulse width modulation (PWM) unidirectional rectifier.

I. INTRODUCTION

TRADITIONALLY, three-phase ac-to-dc high power conversion is performed by diode or phase-controlled rectifiers. Due to the commutation of these structures at the zero crossing of the current, they are also called "line-commutated" rectifiers.

These rectifiers are robust and present low cost, but draw non sinusoidal currents or reactive power from the source, which deteriorate the power quality. To compensate for the harmonic distortion generated by the standard diode rectifiers, passive linear filters or power factor correction structures can be employed [1]–[3].

The multi pulse three-phase rectifiers achieve harmonic cancelation by introducing phase shift by means of special three-phase transformers [4], [5]. Moreover, the simplicity and reliability ability of the diode rectifiers are preserved. However, they are heavy, bulky, and expensive.

Three-phase pulse width modulation (PWM) rectifiers are widely employed in low- and medium-power drive applications where the requirements established by international standards should be satisfied [6]–[8]. These structures are the most promising rectifiers from a power quality viewpoint [1] since they can present low harmonic distortion and unity power factor.

Recent trends in high-power rectifiers have introduced a new class of three-phase rectifiers, the hybrid rectifiers [2], [13]–[15]. The term "hybrid rectifier" denotes the series and/or parallel connection of a line-commutated rectifier and a self-commutated converter [2]. The line-commutated rectifier operates at low frequency and has a higher output power rating. The active rectifier is designed to operate with a small power rating and at a high switching frequency.

In this paper three phase diode rectifier with hybrid unidirectional rectifier is implemented in simulation and results are verified.

II. HYBRID RECTIFIER

The parallel connection of a three-phase diode bridge rectifier and a unidirectional three-phase PWM rectifier is the basis for the hybrid converter, which is shown in the Fig. 1.

The total output power of the hybrid converter is processed largely by the uncontrolled rectifier operating at low frequency while the PWM controlled rectifier, operating at high frequency, only processes about 45% of the power. By doing so, the overall efficiency of the system will increase.

A. Single-Switch Three-Phase Boost Rectifier

The single-switch three-phase boost rectifier, presented in Fig. 2, is the basis for the hybrid converter. It presents a relatively high power factor and is characterized, in general, by a very high utilization of the power components [2], [10]–[13]. However, despite its simplicity and robustness, the current waveforms of this topology do not comply with the IEEE 519 and IEC61000-3-4 standards. The single-switch boost rectifier imposes a rectangular shape to the input current wave-forms. The current control loop can only control the amplitude of these currents while maintaining the output voltage constant under load variations.

To compose the hybrid rectifier, a small modification should be made to the circuit presented in Fig. 2. This modification consists of splitting the boost diode and boost inductor to avoid inappropriate current paths in the system.

The design of these split inductors does not require any special procedure.

B. PWM Unidirectional Rectifiers

Theoretically, any PWM three-phase rectifier can compose the hybrid rectifier. A requirement of the system is that the rectifier be unidirectional shown in fig. 3. The advantage of this topology is that it presents a reduced number of active switches [2], [4].

The main objective of the hybrid rectifier is to obtain perfectly sinusoidal input currents and load sharing characteristics by employing the structures presented in figs. 2 and 3.

The manner in which the currents of the individual converters are combined to generate the resulting harmonics free input current.

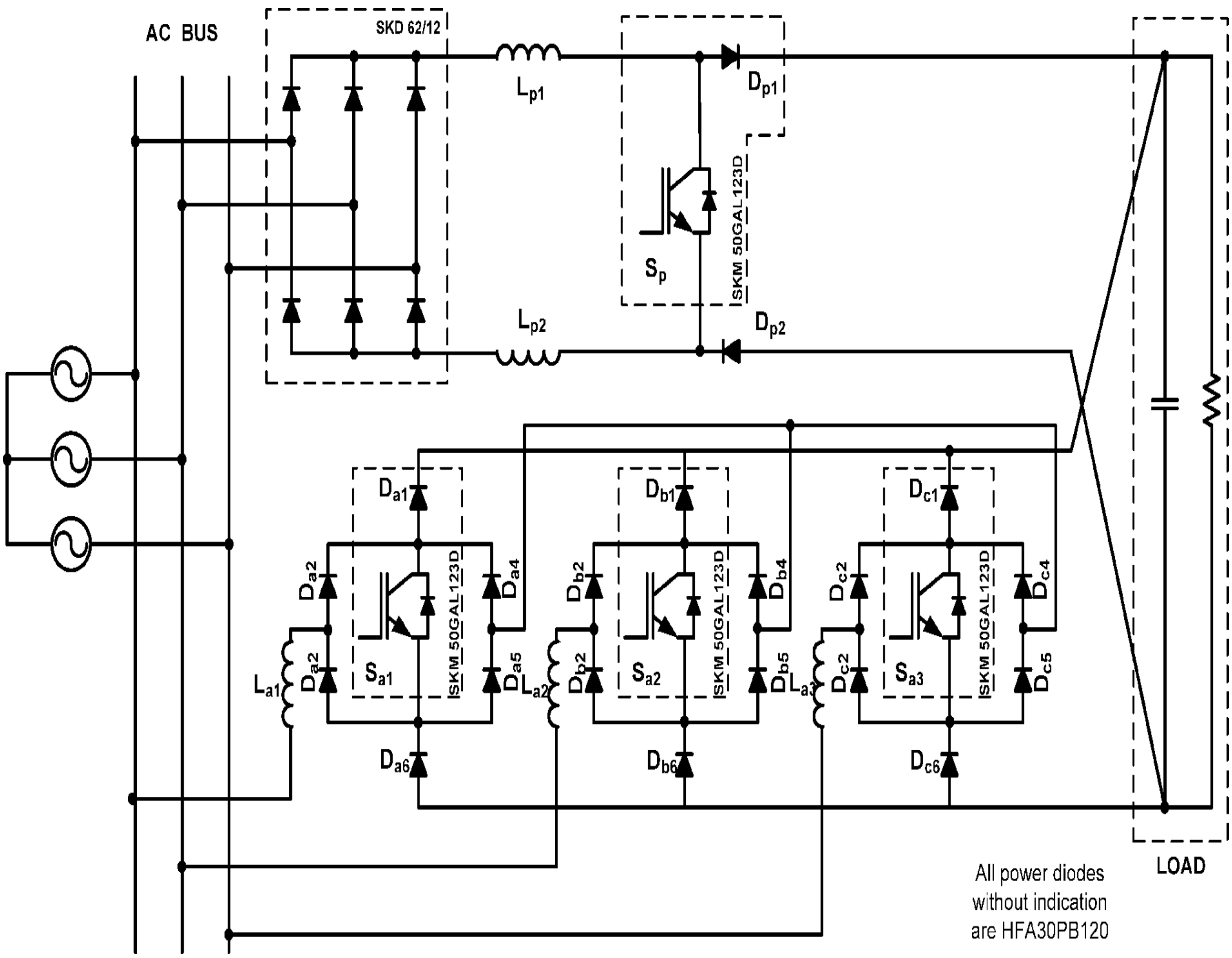

Fig. 1. Hybrid three-phase high -power-factor rectifier. The traditional single-switch three-phase boost rectifier and the three-phase boost unidirectional rectifier connected in parallel.

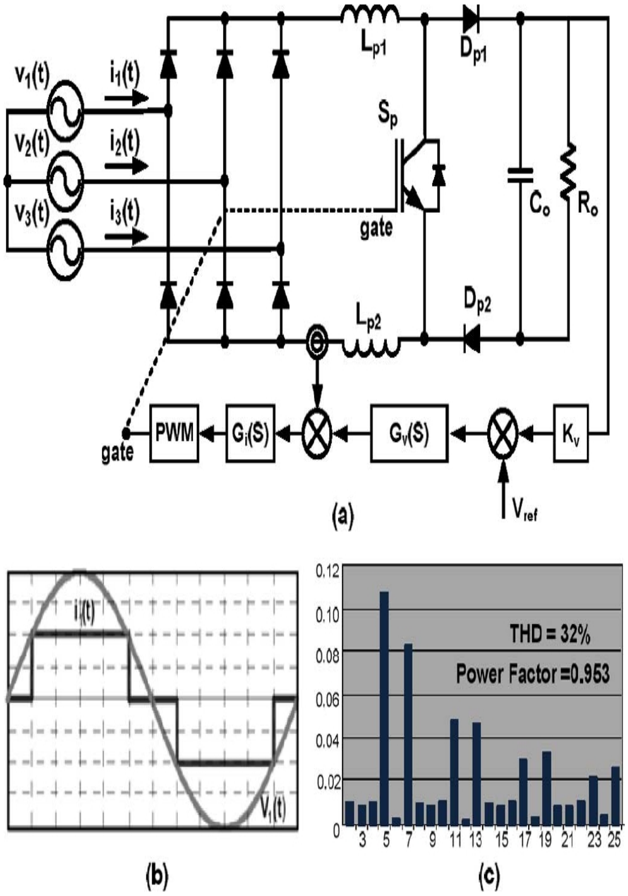

Fig. 2. (a) Single-switch three-phase boost rectifier power stage.

(b) Waveform of the input voltage and current.

(c) Harmonic content of the input current.

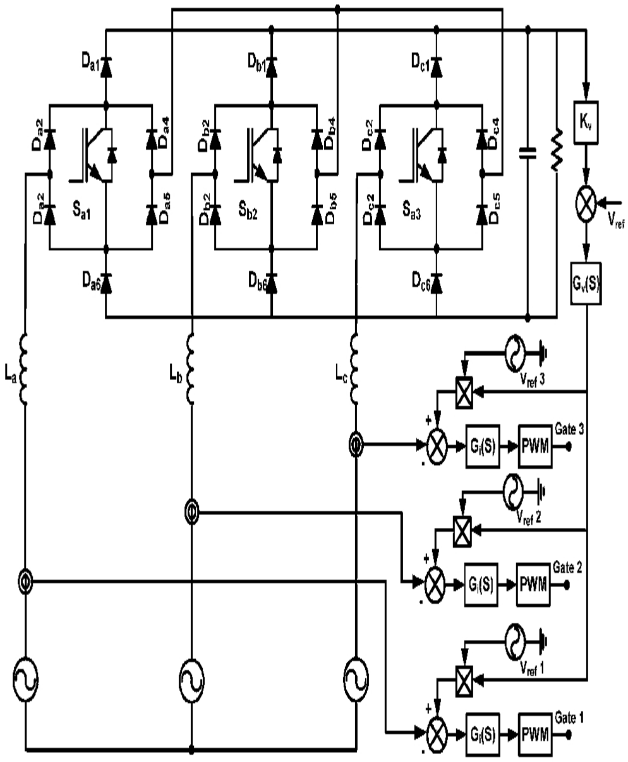

Fig. 3. Unidirectional PWM three-phase rectifier.

III. MATHEMATICAL ANALYSIS

To perform the mathematical analysis from the input currents view point, the output voltage is considered constant. The input voltages and input currents are considered to perfectly sinusoidal are expressed as

$$V_1(t) = V_p \sin(\omega t)$$

$$V_2(t) = V_p \sin(\omega t - 120°)$$

$$V_3(t) = V_p \sin(\omega t + 120°) \text{ and}$$

$$i_1(t) = I_p \sin(\omega t)$$

$$i_2(t) = I_p \sin(\omega t - 120°)$$

$$i_3(t) = I_p \sin(\omega t + 120°) \qquad ...(1)$$

To simplify the analysis, the system is considered loss-free. In this manner, the input active power Pin can be expressed as

$$P_{in} = 3V_pI_p/2 = V_oI_o \qquad ...(2)$$

Where V_p is the peak of the input voltage, I_p is the peak of the input current, P_o is the output power, V_o is the dc output voltage, and I_o is the dc output current.

Substituting (2) into (1) yields

$$i_1(t) = 2I_p \sin(\omega t) / (3V_p)$$

$$i_2(t) = 2I_p \sin(\omega t - 120°) / (3V_p)$$

$$i_3(t) = 2I_p \sin(\omega t + 120°) / (3V_p) \qquad ...(3)$$

The input currents of the hybrid rectifier are obtained by adding the input currents of the passive rectifier [i_{p1} (t), i_{p2} (t) and i_{p3} (t)] and the input currents of the active rectifier [i_{a1} (t), i_{a2} (t) and i_{a3} (t)]. This addition results in

$$i_1 (t) = i_{a1} (t) + i_{p1} (t)$$

$$i_2 (t) = i_{a2} (t) + i_{p2} (t)$$

$$i_3 (t) = i_{a3} (t) + i_{p3} (t) \qquad ...(4)$$

Substituting (3) into (4) yields

$$i_{a1} (t) = 2_{Ip}\sin (\omega t) / (3_{Vp}) - i_{p1} (t)$$

$$i_{a2} (t) = 2_{Ip}\sin (\omega t - 120°) / (3_{Vp}) - i_{p2} (t)$$

$$i_{a3} (t) = 2_{Ip}\sin (\omega t + 120°) / (3_{Vp}) - i_{p3} (t) ...(5)$$

Similarly, at the output, the load current is composed of the sum of currents i_{op} and ion given by

$$i_o (t) = i_{oa} (t) + i_{op} (t) \qquad ...(6)$$

By analyzing the passive rectifier currents of phase 1, the following expression (7) is obtained:

$$I_L(t) = P_{op} / (V_p \ 3 \ v3) \qquad ...(7)$$

Where $I_l(t)$ is the single-switch boost rectifier inductor current and Pop is the active power processed by the passive rectifier.

The power processed by each rectifier is related to the peak value of its input current. According to the concept of the hybrid rectifier, the fact that the diode bridge rectifier processes the greatest part of the output power is more interesting. Evidently, to obtain sinusoidal input currents, an optimal power distribution exists and should be discovered.

Substituting (7) into (5)

$$i_{a1} (t) = 2_{Ip}\sin (\omega t) / (3_{Vp}) - P_{op} \pi (V_p \ 3 \sqrt{3})$$

if $30° \le \omega t \le 150°$

$$i_{a1} (t) = 2_{Ip}\sin (\omega t) / (3_{Vp})$$

if $0° \le \omega t \le 30°$ &

$150° \le \omega t \le 180°$ ...(8)

Due to the unidirectional characteristics of the PWM rectifier, the instantaneous input power should present only positive values.

Analyzing expression (8), the solution that satisfies this condition is presented as

$$P_{op} \le \sqrt{3} P_o / \pi \ 0.522 \ P_o \qquad ...[9]$$

Therefore, the active rectifier's power operation limit is given as

$$P_{op} \ge (1\text{-}0.522)P_o \sim 0.448 \ P_o \qquad ...(10)$$

Where P_{oa} is the active power processed by the PWM rectifier.

Expressions (9) and (10) define the active power sharing between the two converters. If these relationships are not satisfied, the input currents will be distorted.

IV. SIMULATION

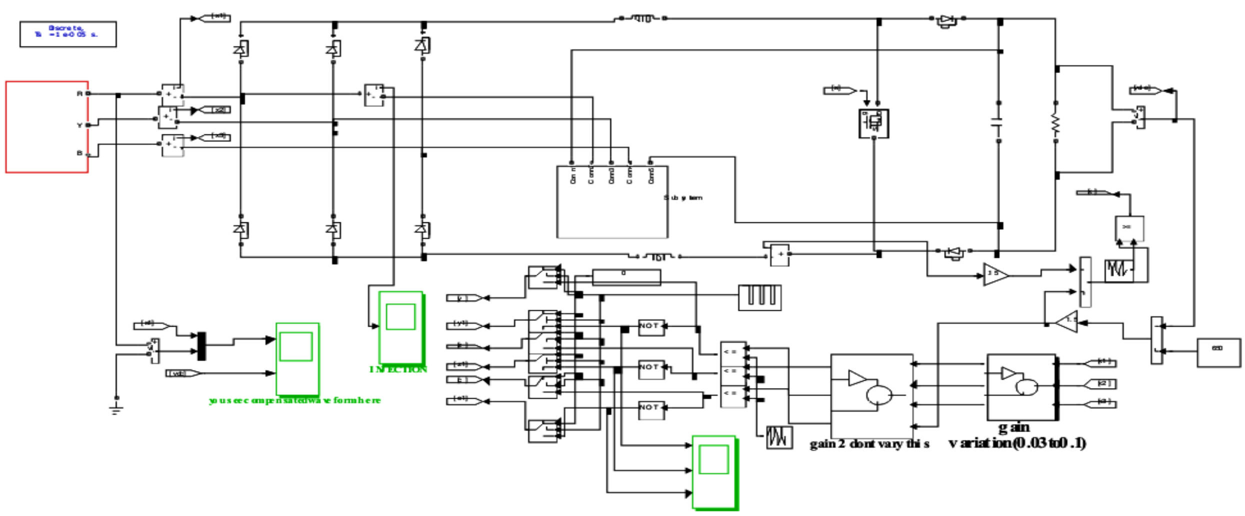

Fig. 4 Simulation diagram of unidirectional hybrid rectifier

The simulation diagram of unidirectional hybrid rectifier is shown in fig. 4. The specifications used in the simulation are presented in Table. I. At first, three phase diode rectifier circuit is alone simulated and source voltages and source currents are obtained. In a second simulation the entire hybrid unidirectional rectifier was simulated with and without pulse width modulation (PWM) three-phase unidirectional boost rectifier and source voltage and current and output voltage for both the cases were obtained.

Table 1. Specifications used in the simulation

S.No	Description	Values
1	Phase voltage	30 volts
2	Output voltage	100 volts Max
3	Unidirectionnel PWM SwitchingFrequency	10KHz
4	Single Switch Boost inductor	2mH
5	Active Rectifier input Inductors	2.5mH
6	Output filter Capacitor	4700uF
7	Output Power	500 watts Max

The dc output voltage regulation is provided by the voltage control loop. The signal obtained at the output of voltage controller is used to adjust the currents references in case the load or input voltage changes.

The inductor current of the single-switch boost rectifier is sampled and compared to a constant reference. The error produced by this comparison is applied to the boost current compensator, and the PWM modulator generates the gate signal of the boost switch.

Currents ia1(t), ia2(t), and ia3(t) are indirectly controlled by sensing the mains currents and comparing them with their respective sinusoidal references. These reference signals must be synchronized with the mains voltages. A good practical solution to obtain these signals is through synchronization transformers connected to the mains to obtain the voltage shape of each phase.

The errors produced by the comparisons between the sampled signals and reference signals are applied to their respective compensators, and the PWM modulators generate the gate signals of the active rectifier.

The source voltage and source current waveforms are shown in Fig. 5. The diode connected in the first phase is conducts from 30 degree to 150 of the input voltage. The diode will not conduct from 0 to 30 degree and 150 to 180 degree. During this period source current become zero and source voltage slightly reduced. The main objective of this paper is to make source current continuous and sinusoidal.

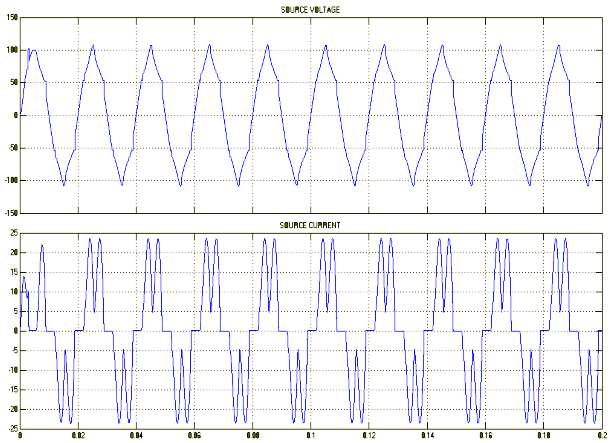

Fig. 5 Simulation Results of three phase 6 pulse rectifier

The waveform for source voltage and source current and output voltage of hybrid unidirectional rectifier was simulated with and without pulse width modulation (PWM) three-phase unidirectional boost rectifier is shown in fig. 6.

Before compensation, the diode connected in the first phase of bridge boost type rectifier conducts only 30 to 150 degree of input supply voltage. So the input current is connected to the load during this period only. From 0 to 30 degree and 150 to 180 degree input current is not connected to the load. Due to this source current become discontinuous and non sinusoidal and also input voltage is slightly reduced. Therefore input supply power factor is reduced and load regulation and load performance is also reduced.

After compensation, the source current is connected to the load continuously through the single-switch diode bridge boost-type rectifier and a pulse width modulation (PWM) three-phase unidirectional boost rectifier. During the period 30 to 150 degree, the load is connected through the single-switch diode bridge boost-type rectifier. During period 0 to 30 degree and 150 to 180 degree, the load is connected through a pulse width modulation (PWM) three-phase unidirectional boost rectifier. Therefore, the entire period 0 to 180 degree, the load is connected. So the source current waveform is improved and become sinusoidal and also source voltage is also improved. Due to this load voltage and load performance is also improved.

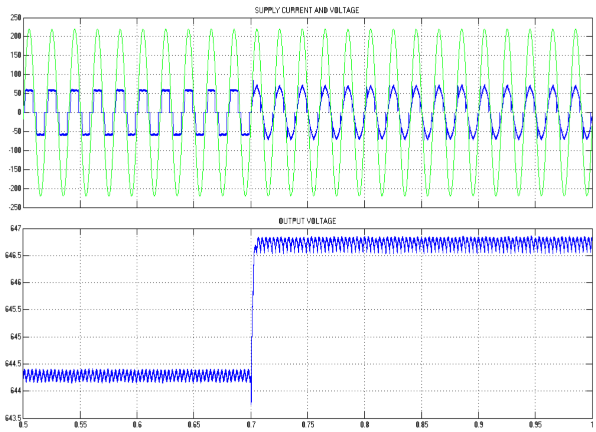

Fig. 6 Simulation Results of hybrid rectifier

Simulation result of injected unidirectional rectifier current is shown in fig. 7.

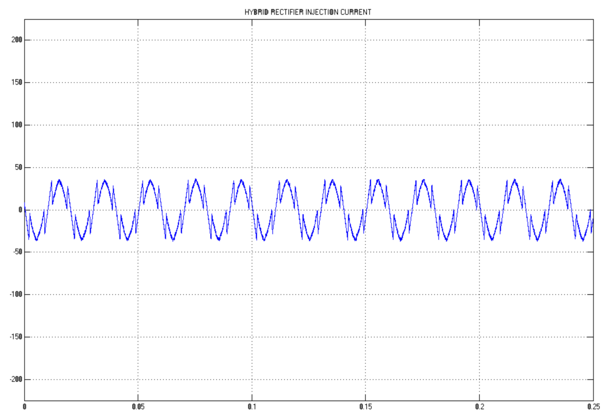

Fig. 7 Simulation result of injected unidirectional rectifier current

V. HARDWARE DESCRIPTION

The hybrid three-phase rectifier is originated by the parallel connection of a three-phase diode bridge rectifier and a bidirectional Boost-type three-phase PWM rectifier. A diagram of the circuit generation of the proposed hybrid rectifier is presented in Fig. 8. However, it is not possible to connect the both rectifiers directly due to the step up characteristic of the Boost-type PWM rectifier. Thereby, the hybrid configuration should employ a circuitry to connect the both rectifiers.

This circuit can be connected in the AC-side or in the DC-side of the hybrid rectifier. The AC-side connection is performed by means of a three phase transformer (or autotransformer.) The hybrid rectifier generated with the AC-side connection is presented in Fig. 9. In this case, the outputs are directly connected; the AC-side connection works in low frequency and it did not allow the output voltage control. Otherwise, the DC-side connection can be performed by means of a DC-DC Boost converter. The hybrid rectifier generated with the DC-side connection is presented in Fig. 10. In this hybrid rectifier, the inputs are directly connected; the DC-side connection works in high frequency and it allows the output voltage control. Split Boost inductors and split Boost diodes are necessary to avoid inappropriate current paths in the rectifier.

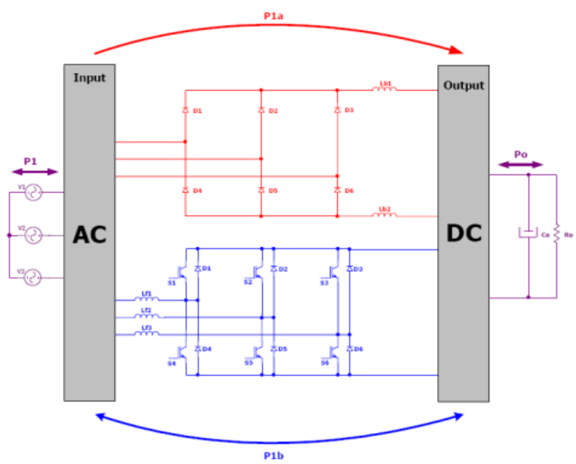

Fig. 8. Circuit generation of the proposed hybrid rectifier

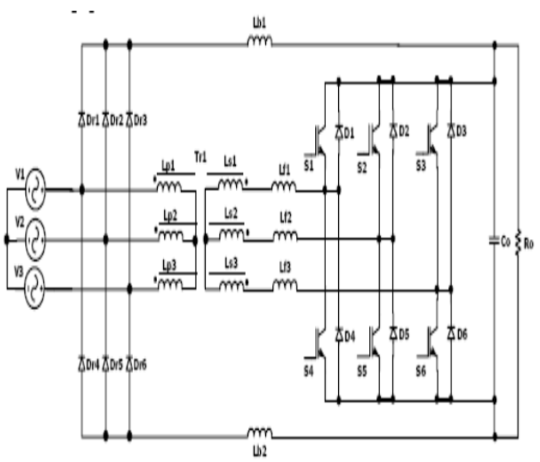

Fig. 9. The bidirectional hybrid three-phase rectifier employing autotransformer

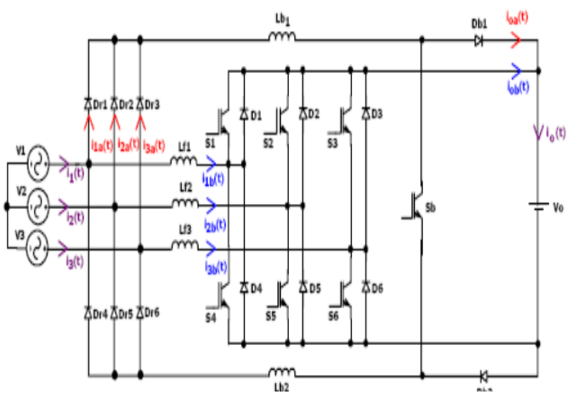

Fig. 10. Proposed bidirectional hybrid three-phase rectifier employing Boost converter

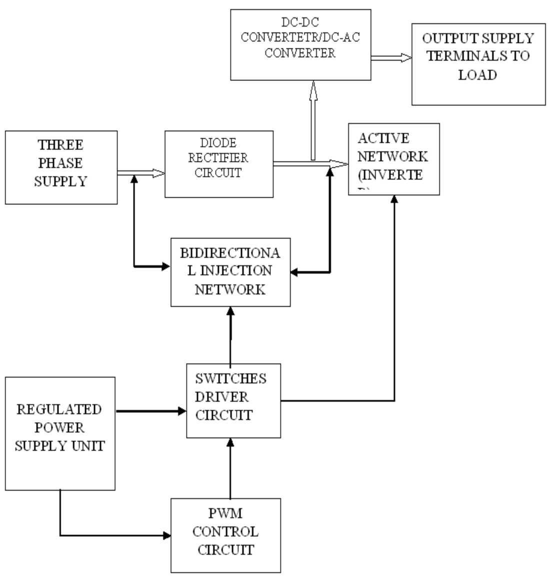

Fig. 11 Functional block diagram

The functional block diagram of hybrid rectifier is shown in fig. 11. It consists of diode rectifier, bidirectional injection network, driver circuit and PWM control circuit. The bidirectional injection network is connected across the diode rectifier. The detailed circuit diagram of AC-DC PWM Boost Rectifier and AC-DC Unidirectional Rectifier are shown in fig. 12 and 13 respectively.

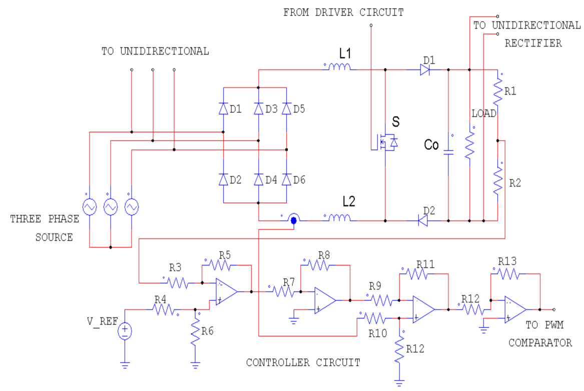

Fig. 12 AC-DC Pwm Boost Rectifier

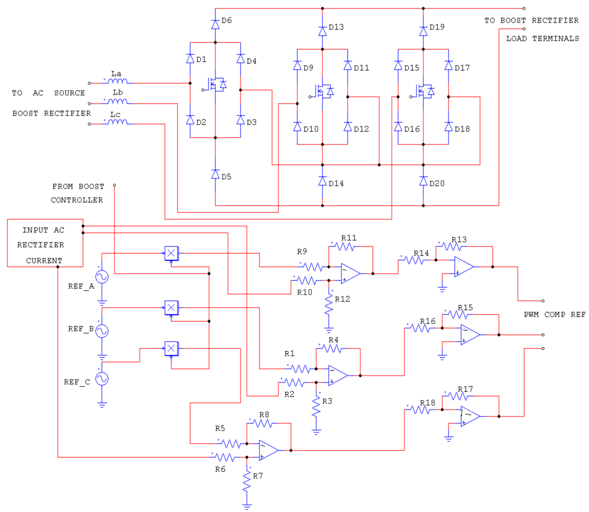

Fig. 13. AC-DC Unidirectional Rectifier

This paper describes the conception and analysis of a unidirectional hybrid three-phase rectifier suitable for medium and high-power applications. The rectifier is composed of a single-switch diode bridge boost-type rectifier in parallel with a Pulse Width Modulation (PWM) three-phase unidirectional boost rectifier. The objective is to obtain a structure capable of providing sinusoidal input currents with low harmonic distortion and dc output voltage regulation.

The diode rectifier operates at low frequency and has a higher output power rating. Therefore, the PWM unidirectional rectifier is designed to operate with a small power rating and at a high switching frequency. The rectifier topology conception, principle of operation, control scheme, and simulation and hardware description are also presented in this paper.

The injection networks of the converter do not process all the power delivered to the load, resulting in a very efficient alternative.

VI. CONCLUSION

A novel three-phase hybrid rectifier for high-power applications was presented in this paper. The structure is composed of a passive rectifier in parallel with an active rectifier. The fact that each rectifier is responsible for processing approximately 50% of the output power improves the robustness of the power converter and guarantees a high efficiency.

The adopted control strategy regulates the output voltage and controls the input currents to achieve high power factor. The increase in the component count due to the use of two rectifier topologies does not greatly affect the volume, since the components are designed for the half of the output power.

The advantage of this hybrid system is its capability of processing high power levels due to the parallel connection of the rectifiers. The increase in the efficiency is another expected advantage.

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