MODULAR ISOLATED BOOST CONVERTER WITH A NEW HARMONIC REDUCTION TECHNIQUE

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Abstract: The mains current in an ac-dc converter contains periodic current pulses due to the action of rectifier and output filter capacitor. The high current peaks cause harmonic distortion of the supply current and low power factor. This results in a poor power quality, voltage distortion, poor power factor at input ac lines, varying rippled dc output at load end and low efficiency. The objective of this work is to find out method to reduce the harmonics in the source current and to improve the power factor i.e., ultimately reducing the total harmonic distortion in supply current. Then we will see a hybrid three phase rectifier and how it is capable to achieve high input power factor and low total harmonic distortion of input currents (THD). The proposed rectifier is having single phase isolated boost rectifiers in parallel to each leg of existing diode bridge rectifier with some load. This topology results in a structure capable of programming the input current waveform and providing conditions for obtaining high input power factor and low harmonic distortion in current. In order to validate the proposed model, a 2.2kW load model is simulated and results are presented here.

Key words: Average current mode controller, Hybrid multipulse rectifier (HMPR), Isolated boost rectifier, Power factor correction circuit (PFC)

1. Introduction
1.1 Modular approach

There are three different types of power supply architectures. They are centralized power systems, modular power systems and distributed power system (employing modular design).A distributed power system (DPS) offers many advantages from the standpoint of high power capability, reliability, modularity, redundancy and maintainability. As a result, DPS has become rather popular in telecom and server applications. For centralized power supplies, the reliability must be very high, since a failure would cause the entire system to shut down. However, the failure of any power module in a DPS has a reduced effect on the overall system because of the built in N+1 redundancy, where N is the minimum number of modules needed to supply the load. Additional advantages of DPS are rapid replacement of faulty modules and flexibility to expand the system capacity as the load requirements increase.

Despite several important advantages, a DPS offers two major drawbacks: (1) extra cost and (2) noise caused by several converters placed next to each other. Thermal issues may arise because the power supplies are either compressed into ever-smaller cases or because they are mounted on the logic boards to which they supply power. Nevertheless, paralleling decreases the dissipation per module because each module is required to handle less power in the system, which helps simplify thermal design. Front end converters for DPS applications are typically used in telecom and server applications. There is a wide range of front end converters available in the market for telecom applications, with power levels ranging from hundreds of watts to several kilowatts. For server applications, the typical power level is 1kW. However, the market for server applications is growing quickly, as is the power level required for such applications. As predicted in the past, computer applications will continue to drive the power supply industry and to promote the widespread use of DPS. It is incorporating the advantages of modular power system. However, all outputs of front end converters go to the intermediate bus by paralleling technology [1-3].

1.2 Effect of harmonics

Harmonics can cause overloading of conductors and transformers and overheating of utilization equipment such as motors. Triplen harmonics can especially cause overheating of neutral conductors on 3-phase, 4-wire systems. While the fundamental frequency and even harmonics cancel out in the neutral conductor, odd order harmonics are additive. Even in a balanced load condition, neutral currents can reach magnitudes as high as 1.73 times the average phase current. This additional loading creates more heat, which breaks down the insulation of the neutral conductor. In some cases, it can break down the insulation between windings of a transformer. In both cases, the result is a fire hazard. But this

potential damage can be diminished by using sound wiring practices [4-7].

1.3 Boost converter

By using the boost converter, it is possible to shape the input current drawn by the rectifier bridge to be sinusoidal and in phase with the input voltage. The choice of power electronic converter is based on the following considerations.

• In general, electrical isolation between the utility input and the output of the power electronic system either is not needed or it can be provided in the second converter stage, as in the switch-mode dc power supplies.

• In most applications it is acceptable, and in many cases desirable, to stabilize the dc voltage is slightly in excess of the peak of the maximum of the ac input voltage.

• The input current drawn should ideally be at a unity power factor so that the power electronic interface emulates a resistor supplied by the utility source. This also implies that the power flow is always unidirectional, from the utility source to the power electronic equipment.

• The cost, power losses and size of the current shaping circuit should be as small as possible.

Since, the boost converter is satisfying the above conditions so boost and its derived topologies are generally employed in front end converters.

2. Proposed converter

2.1 Introduction

As we have discussed the DPS is having special front end converter (many more are proposed currently) to improve the distribution of electrical energy at the same time meeting power quality standards. But 3φ diode bridge rectifiers continue to be very popular in several industrial and rural applications where an intermediate dc link provides energy for other electronic circuits. However, such standard diode bridge rectifiers do not meet harmonic current content restrictions as imposed by several international standards such as IEC61000 & IEEE 519. Thus, expensive and bulky passive filters or complex power factor correction (PFC) and active filter structures must be installed to compensate the inherent harmonic current distortion.

Multi-pulse rectifiers applied in three phase applications for mitigation of the input current harmonic content. Which need magnetic circuits such as multiphase transformers, inter phase transformers, current balancing transformers or harmonic blocking transformers. Those are complex, heavy, bulky and expensive. A simplified transformer concept for multipulse rectifier

application compose the input line current waveform, a power transformer with a rating of 1.16 P_{out} (where P_{out} is the nominal value of output power) was necessary. Such a device contributes for increased cost, weight and size of the structure [8].

A novel approach that overcomes such disadvantages is presented here. We propose a new structure composed of a single-phase isolated boost rectifier associated in parallel with each leg of a three-phase six-pulse diode rectifier resulting in a programmable input line current waveform structure. The overall converter behaves as a current source controlled with a suitable strategy, i.e., the imposition of a suitable input line current waveform in order to provide low THD_I. The system is a programmable PFC based hybrid multi-pulse power rectifier (PFC-HMPR) deploying isolated boost converters. The proposed structure is depicted in Fig.2. This system is capable of providing clean power without using multiphase transformers, inter phase transformers, current balancing transformers and harmonic blocking transformers. But only isolation transformers are required which are comparatively of low power rating.

2.2 Overview of three phase diode bridge rectifier

When balanced three phase sinusoidal voltage source is fed to a constant load current through diode bridge rectifier then load draws a constant phase current of 120° duration in each positive and negative half cycle. Hence due to this constant and discontinuous line current harmonics are introduced in to the utility disturbing other loads and declining the power quality [9-10].
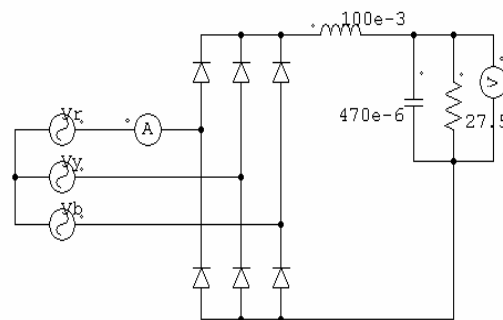

Fig.1 Diode bridge rectifier

The diode bridge phase current will be as shown in the fig.1. In this circuit we have connected a 2.2KW, 246V resistive load which draws a 9A constant load current.

2.3 Theory of operation of PFC-HMPR

Fig.2 shows the PFC-HMPR which is composed by a standard three-phase six-pulse diode

rectifier, indicated in the block diagram as Rect-1, and single-phase isolated boost rectifiers associated in parallel to each phase of diode-bridge rectifier leg.
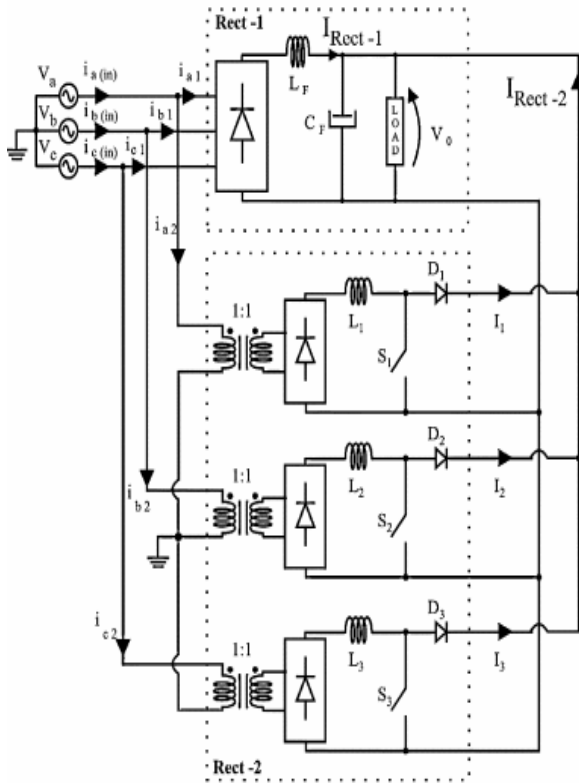

Fig. 2 Three phase PFC hybrid power multipulse rectifier (PFC-HMPR) deploying boost converters fed through single-phase isolating transformers[13]

Fig. 2 shows the principle of constructing an input line current through two components i_{a1} and i_{a2}, obtained $I_{a(in)}$ when the PFC-HMPR topology operates as a conventional three-phase twelve-pulse rectifier which is the focus of this work.

I_{a2} reference current is the main controller of the overall characteristic of the final input line current waveform. The proposed PFC-HMPR allows the improvement of the input line current $I_{a\ (in)}$ by reducing its THD. It is important to not that, only a fraction of the total output power flows through the isolated boost parallel circuits, supporting a competitive economic impact.

When PFC-HMPR operating as a conventional twelve-pulse rectifier, just about 20% of the total output power is processed by the isolated boost rectifiers and a THD_I less than 15% in the input line current can be achieved. For example, if a controlled waveform as indicated in Fig.3 is imposed through the Isolated boost parallel rectifiers, the input line current $I_{a(in)}$, will be built of the combination of i_{a1}

and i_{a2} with a very low THD_I (around 6%), it supplies about 51% of the rated power.

a) Twelve pulse ac input current waveform PFC-HMPR.

When PFC-HMPR operating has to work as a 12-pulse rectifier, the reference current I_{a2} must be as shown in Fig.3. In this configuration only 20% of output power is processed by the isolated boost rectifiers and a THD_I less than 15% in the input line current is achieved. Hence, for the given power rating of diode bridge rectifier we can raise the output load by 25% i.e., up to 125% of earlier load. There are few ways to reduce the source current harmonic distortion. By forcing the current through the inductor of auxiliary isolated boost converter (i_{a2}) we are ultimately forcing the source current to follow the imposed reference wave form.
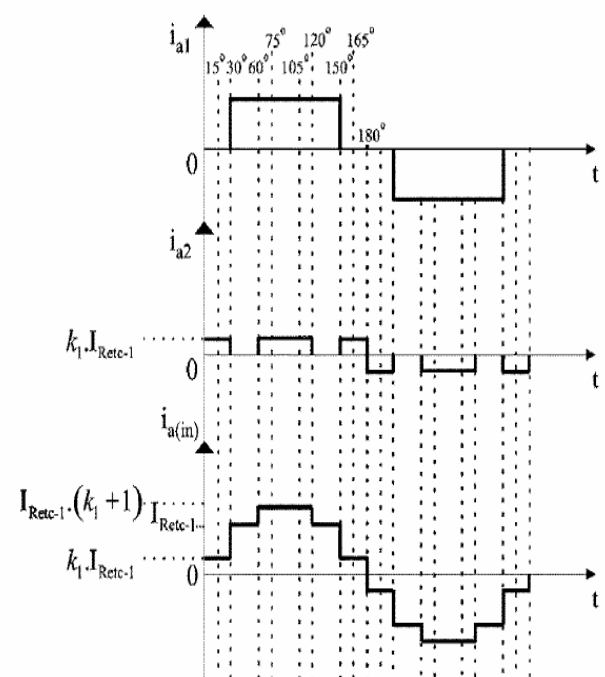

Fig. 3 Theoretical waveforms of 12 pulse rectifier [13]

b). Twenty Pulse Ac Input Current Waveform PFC-HMPR

When PFC-HMPR operating has to work as a 12-pulse rectifier, the reference current I_{a2} must be as shown in fig. 4. In this configuration only 21.75% of the output power is processed by the isolated boost rectifiers and a THD_I less than 12.24% in the input line current is achieved. Hence, for the given power rating of diode bridge rectifier we can raise the output load by 27.8% i.e., up to 127.8% of earlier load.
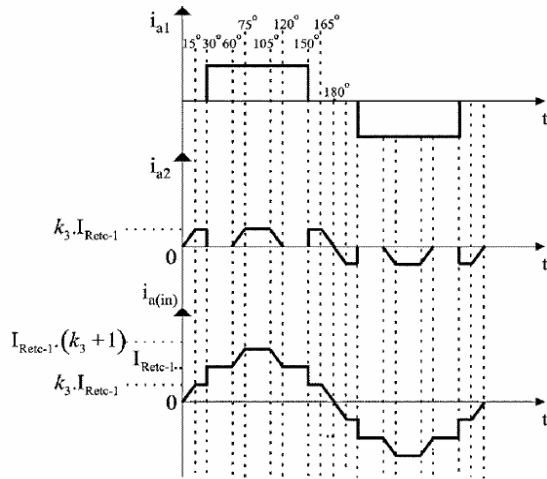
Fig. 4 Theoretical waveform of 20 pulse source current

By forcing the current through the inductor of auxiliary isolated boost converter (i_{a2}) we are ultimately forcing the source current to follow the imposed reference wave form.

c) Sinusoidal ac input current waveform PFC-HMPR

When PFC-HMPR operating has to work as a sinusoidal-pulse rectifier, the reference current I_{a2} must be as shown in Fig.5. In this configuration only 51.4% of the output power is processed by the isolated boost rectifiers and a THD_I less than 5.97% in the input line current is achieved. Hence, for the given power rating of Diode Bridge rectifier we can raise the output load by 105.6% i.e., up to 205.6% (theoretically) of earlier load.
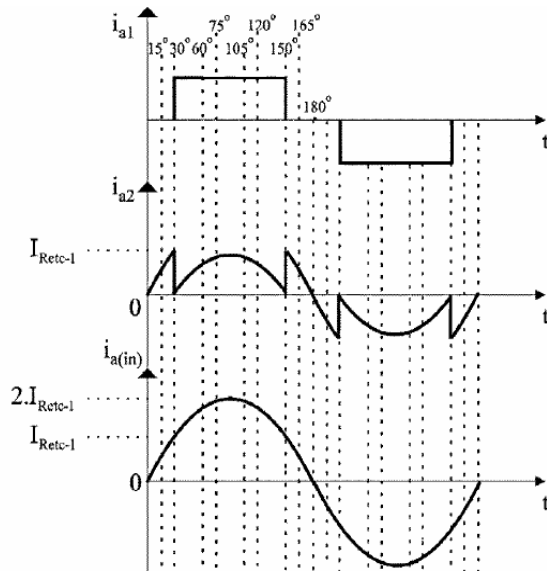

Fig. 5   Theoretical sinusoidal line current

By forcing the current through the inductor of auxiliary isolated boost converter (i_{a2}) we are ultimately forcing the source current to follow the imposed reference wave form.

The proposed hybrid rectifier can operate in accordance to the harmonic content restrictions of the input line current with the isolated boost rectifiers processing just the minimum power. Moreover, the economical benefits of this new topology are extremely valuable for high power installations, because around 33% maximum value of rated power will be processed in the parallel circuits, in order to reduce the THD_I to a very low value (around 5%). Moreover, when used in retrofitting applications, the available total rated power will increase to 133% of the original output power, with obvious improvements on power quality.

d) Motivation to use boost converter

Boost converters have been traditionally used as front-end wave shaping systems because of following advantages:
• In most applications it is acceptable, and in many cases desirable, to stabilize the dc voltage V_d slightly in excess of the peak of the maximum of the ac input voltage.
• The input current drawn should ideally be at a unity power factor so that power electronic interface emulates a resistor supplied by the utility source. This also implies that the power flow is always unidirectional, from the utility source to the power electronic equipment.
• The cost, power losses and size of the current shaping should be as small as possible.

In order to be applied as parallel path of three-phase six-pulse diode bridge rectifier, non-isolated Boost converters are not suitable because during the period of time where the input line voltage of the three-phase power source is higher than the dc output voltage, the boost current keep increasing even when the switch is open. In fact, when the Boost switch is open and the freewheeling diode is forward biased and connecting the path between Rect-2 and Rect-1, the Boost current flows through the diodes of the three-phase six-pulse rectifier bridge (Rect-1) and its control is lost.

The boost current is confined to the secondary winding circuit and the dc link voltage is kept with average value approximately equal to the peak line voltage value. Here Boost current will be forced to return through the Boost circuit instead of the three-phase six-pulse rectifier bridge. The leakage

inductance & resistance of winding should be as small as possible. If not at the zero crossing of the voltage of source boost current will not follow expected reference waveform but varies linearly.

3. Proposed control technique

The main control circuit objective is to impose the input line current at low THD and high input power factor for the proposed PFC-HMPR. Therefore, the control strategy must focus on establishing the best relationship between the input current i_{a1} of the standard three-phase six-pulse diode bridge rectifier(Rect-1), and the input current i_{a2} of the controlled Isolated boost rectifier (Rect-2), in order to achieve a desirable input line current THD.

3.1 Control strategy for 12- pulse ac input current waveform

As example, if a twelve pulses ac current waveform is desired, the control strategy of the controlled isolated boost rectifiers (Rect-2) can be established as shown in the diagram of fig. 6.
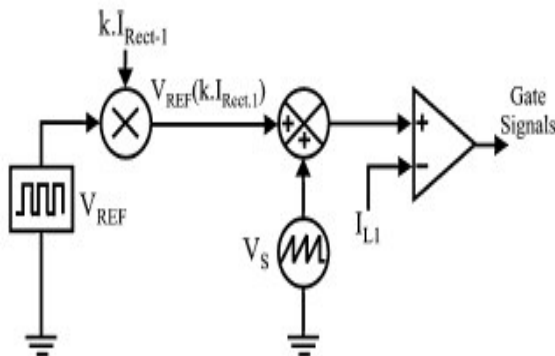

Fig.6 Proposed control strategy for 12-pulse input line current waveform.

In order to compose the waveform of the input line current $I_{a(in)}$, a sample of the input line-to-neutral voltage (V_a) must be rectified and compared with dc voltage levels in order to generate a synchronized square wave (V_{REF}) to impose the input Isolated boost current (I_{a2}) depicted in Fig. 3. The voltage V_{REF} is the reference current waveform and can be supplied either by analog or digital devices. It was found that, when operating as a conventional 12-pulse rectifier, the lowest input line current THD is achieved when the magnitude of the current I_{a2} (Rect-2) is 33% of the magnitude of the current I_{Rect-1} (Rect-1). Therefore, the reference voltage V_{REF} must be multiplied by a fraction of the current $(I_{Rect-1}$) of Rect-1 providing a reference signal equal to $V_{REF} \times (k \times I_{Rect-1}$), where k is equal to 1/3 of the dc current through the output inductor filter $(L_F)$of the three-phase six-pulse diode rectifier (Rect-1) for the minimum T_{HDI}.

In order to generate a PWM reference signal, a saw tooth voltage waveform V_s is added to the multiplier circuit signal. Finally, the PWM reference signal must be compared with the current flowing through the inductor L_1 of isolated boost converter (Rect-2) to generate the gate-drive signal for switch S_1. Hence, the current through the inductor L_1 will follow the imposed reference through a very simple PWM control strategy [11-14].

3.2 Control strategy for twenty pulse input current waveform

For 20 pulse ac input current waveform the control strategy of the controlled isolated boost rectifiers (Rect-2) can be established. In order to compose the waveform of the input line current $I_{a(in)}$, a sample of the input line-to-neutral voltage (V_a) must be rectified and compared with dc voltage levels in order to generate a synchronized step wave $(V_{REF}$) to impose the input Isolated boost current (I_{a2}) depicted in fig. 4. The voltage V_{REF} is the reference current waveform and can be supplied either by analog or digital devices. It was found that, when operating as a conventional 20-pulse rectifier, the lowest input line current THD is achieved when I_{a2} (Rect-2) is k1 & k2 times of the magnitude of current I_{Rect-1} (Rect-1). Therefore, the reference voltage V_{REF} is obtained by the current I_{Rect-1} of Rect-1 with k1 & k2 providing a reference signal leading to produce a waveform as shown in Fig.4, hence leading for minimum T_{HDI}.

In order to generate a PWM reference signal, a saw tooth voltage waveform V_s is added to the multiplier circuit signal. Finally, the PWM reference signal must be compared with the current flowing through the inductor L_1 of isolated boost converter (Rect-2) to generate the gate-drive signal for switch S_1. Hence, the current through the inductor L_1 will follow the imposed reference through a very simple PWM control strategy.

3.3. Control strategy for sinusoidal ac input current waveform

For sinusoidal ac input current waveform the control strategy of the controlled isolated boost rectifiers (Rect-2) can be established in the fig 3. In order to compose the waveform of the input line current $I_{a(in)}$, a sample of the input line-to-neutral voltage (V_a) must be rectified and compared with dc voltage level in order to generate a synchronized reference wave (V_{REF}) as shown in fig.5 to impose the input isolated boost current (Ia2) depicted in fig.3. The voltage V_{REF} is the reference current waveform and can be supplied either by analog or

digital devices. It was found that, when operating as a sinusoidal hybrid multi pulse rectifier, the lowest input line current THD is achieved when the magnitude of the I_{a2} (Rect-2) current is equal to the magnitude of the current I_{Rect-1} (Rect-1). Therefore, the reference voltage V_{REF} can be directly taken without any fraction of I_{Rect-1} (Rect-1) leading to produce a waveform as shown in Fig. 5, hence leading for minimum T_{HDI}.

In order to generate a PWM reference signal, a saw tooth voltage waveform Vs is added to the multiplier circuit signal. Finally, the PWM reference signal must be compared with the current flowing through the inductor L_1 of Isolated boost converter (Rect-2) to generate the gate-drive signal for switch S_1. Hence, the current through the inductor L_1 will follow the imposed reference through a very simple PWM control strategy.

From the analysis on output results, we can infer that as the processing over input current, we can achieve the required wave form with restricted THD at the cost of efficiency(η) of converters because of increasing switching losses. Hence to increase the efficiency (η) of the converter that is to decrease the switching losses we have to soft switching techniques such as ZVS, Resonant switching etc.

4. Results

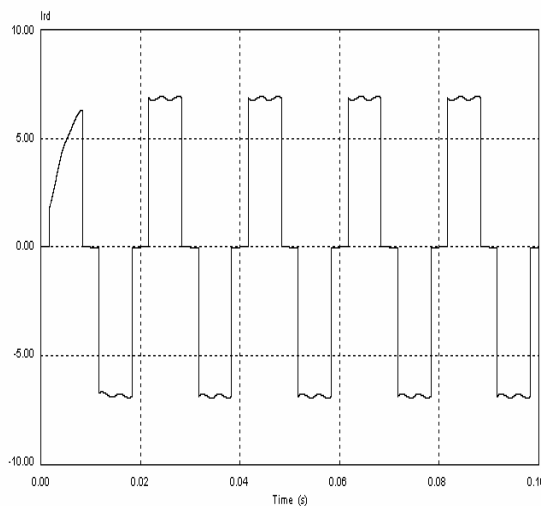4.1 Twelve pulse ac line current HMPR

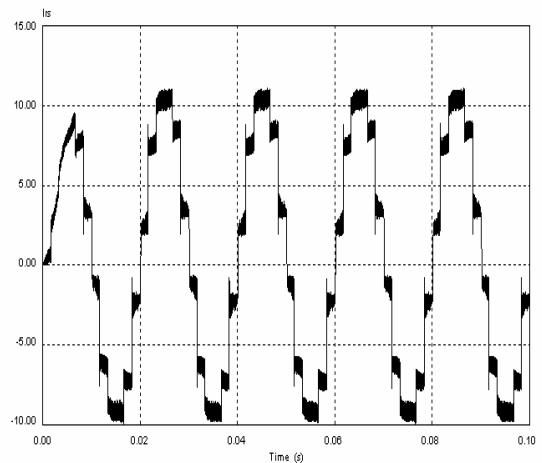Fig.7 Line current of diode bridge rectifier
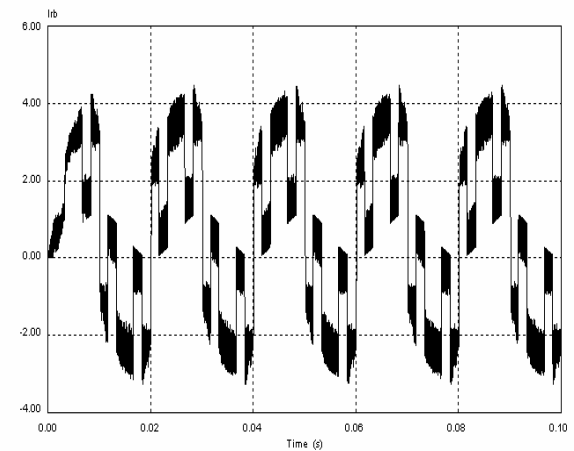

Fig.8   Isolated boost rectifier current

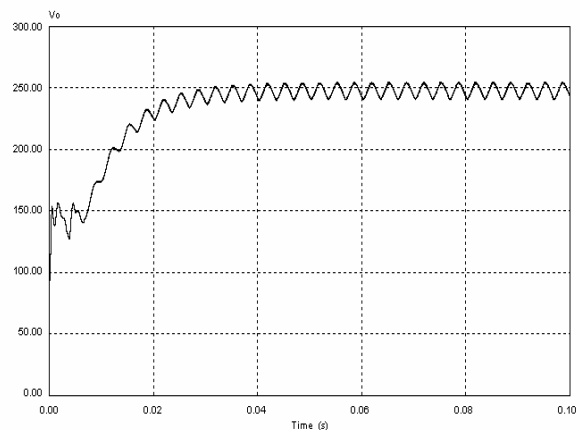Fig. 9 Isolated boost rectifier current

Fig. 10 Output voltage of 12 Pulse HMPR

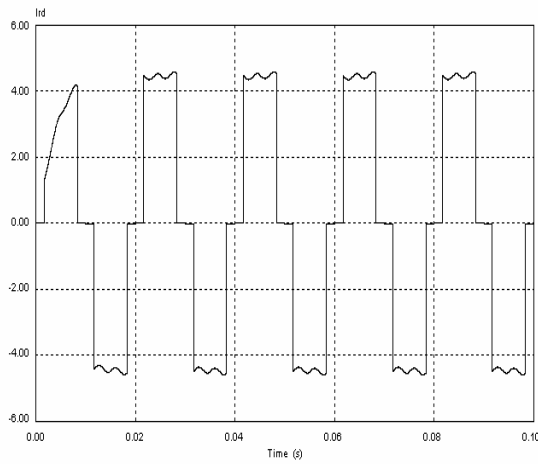### 4.2 Twenty pulse ac line current HMPR
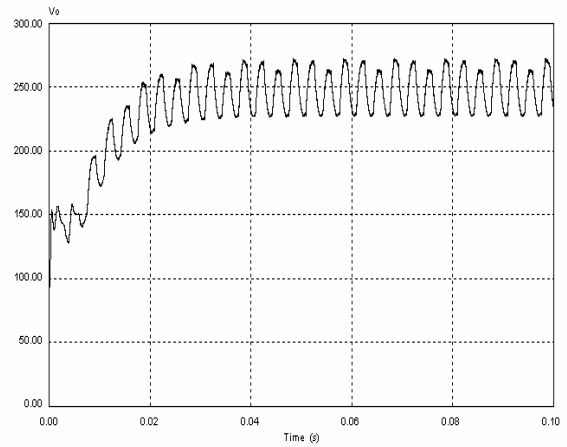

Fig. 11 R $_{Line}$ diode bridge rectifier

Fig. 14 Output voltage waveform

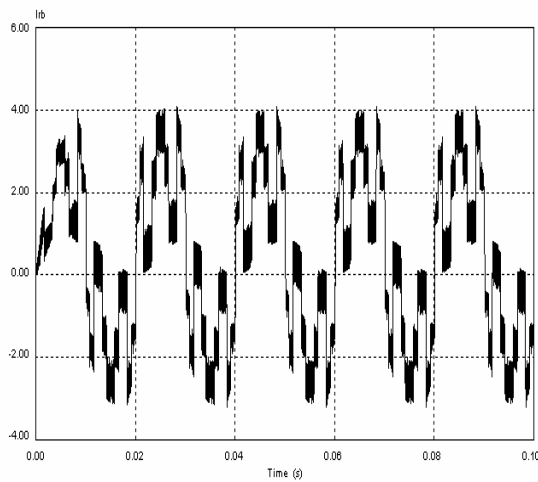### 4.3. Sinusoidal pulse ac line current HMPR
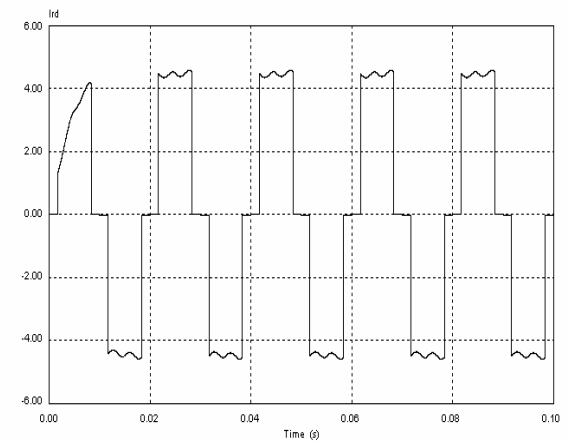

Fig. 12 R_{ph} boost current (I_{rh})

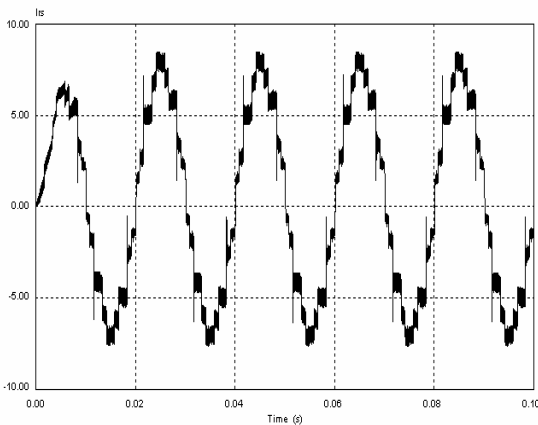Fig. 15 Diode Bridge R_{ph} Line current I_{rrl}

Fig. 13 Source R_{ph} Line current
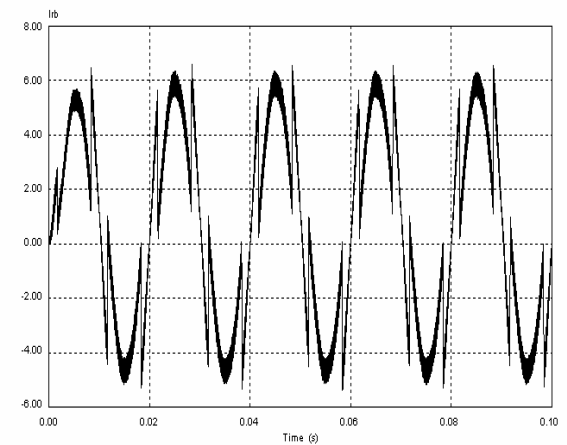

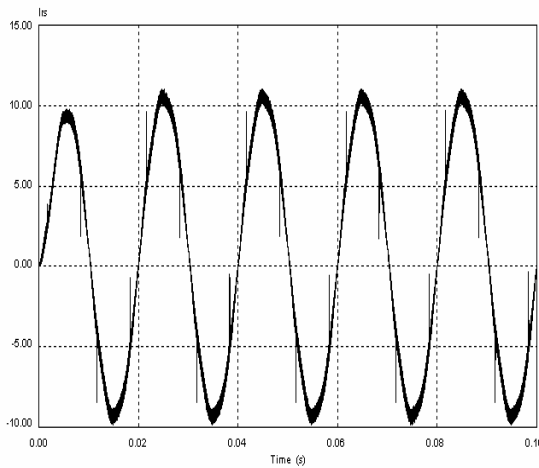Fig. 16 R_{ph} Isolated boost current (I_{rb})

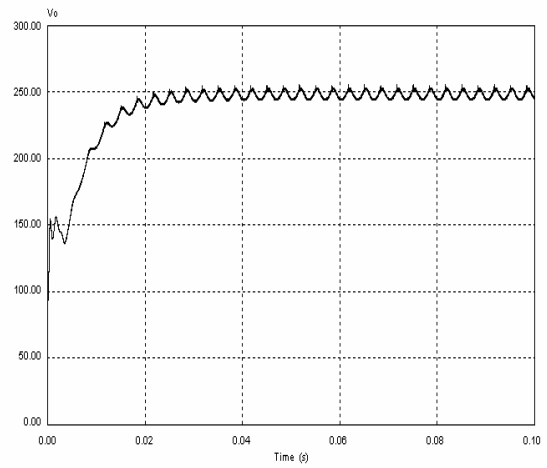Fig.17 R_{ph} Source Current (I_{rs})

Fig. 18 Output voltage waveform

4.4   Calculated total harmonic distortion for various values of K

Table 1

Twelve pulse rectifier

S. No	K	$I_{1fundamental}$		I_3 %	I_5 %	I_7 %	THD	V_o (V)
		Peak	R.m.s					
1	1/1.8	10.12	7.156	1.81	5.28	4.21	15.73	246
2	1/2	10.11	7.149	1.62	3.39	2.98	14.92	246
3	1/3	10.1	7.145	1.13	3.14	2.8	15.14	246
4	1/4	10.09	7.138	0.95	6.87	5.17	17.26	246.5
5	1/5	10.091	7.134	0.87	9.31	6.84	19.25	246.5

Table 2

Twenty pulse rectifier

S. No	K_1	K_2	$I_{1fundamental}$ (A)		I_3 %	I_5 %	I_7 %	THD	V_o (V)
			Peak	R.m.s					
1	0.33	0.25	10.16	7.184	2.2	6.43	4.08	12.9	246
2	0.28	0.18	10.15	7.18	1.5	2.18	4.18	12.25	246
3	0.27	0.18	10.15	7.178	1.5	1.82	5.05	12.2	246

Table 3

Sinusoidal pulse rectifier

S. No	K	$I_{1fundamental}$ (A)		I_3%	I_5%	I_7 %	THD	V_o (V)
		Peak	R.m.s					
1	1	10.25	7.246	1.38	0.69	1.44	5.97	246

From table 1it is clear that the auxiliary circuit (Rectifier -2) in this 12 pulse HMPR is taking 20.6% of output load. So, the burden on the main diode bridge rectifier is reduced and also for the same power rating of Diode bridge (Rectifier-1) circuit we can go for 125% of earlier load. Which is more than the alone diode bridge rectifier. Here reduction in efficiency is acceptable. Hence, the capital cost expended in connecting extra auxiliary circuit is saved with in due course of time.

From the above table we can infer that at K=1/3 the 3rd, 5th & 7th harmonics are appreciably small and Total Harmonic Distortion is also overall minimum. Hence we have taken optimum value for K i.e., 1/3 and the simulated results are presented here.

From table 2, the auxiliary circuit (Rectifier -2) in this 20 pulse HMPR is taking 21.75% of output load. So, the burden on the main diode bridge rectifier is reduced and also for the same power rating of Diode bridge (Rectifier-1) circuit we can go up to 121.75% of earlier load (only diode bridge rectifier), which is certainly even more than the 12 pulse HMPR. Here the reduction efficiency is acceptable. Hence, the capital cost expended in connecting extra auxiliary circuit is saved with in due course of time.

From the above table when K_1=0.27 & K_2=0.18 3rd, 5th & 7th harmonics are appreciably small and total harmonic distortion is minimum. Hence we have chosen optimum values of k_1 & k_2 to be 0.27 & 0.18 respectively and its simulation results are presented here.

From table 3, the auxiliary circuit (Rectifier -2) in this sinusoidal pulse HMPR is taking 51.4% of output load. So, the burden on the main diode bridge rectifier is reduced and also for the same power rating of diode bridge (Rectifier-1) circuit we can go up to 205.6% of earlier load, which is much more than all the above HMPR techniques. Hence, the capital cost expended in connecting extra auxiliary circuit is saved with in due course of time.

In sinusoidal pulse HMPR configuration requires three single phase transformers each rating approximately 57.8% of load rating. Hence, the circuit becomes large in space, bulky, less reliable due to heating of transformer, noisier comparatively than above two techniques and complicate to implement the logic. However, efficiency can be improved by soft switching techniques. Hence, this technique is economical only when output load has to double.

5. Conclusion

In this technique we have improved the Power factor and harmonic content in three phase supply of three phase diode bridge rectifier by connecting three auxiliary circuits (Isolated Boost) in parallel to existing three phase diode bridge rectifier, it is called Hybrid Multi-Pulse Rectifier (HMPR). In this technique, we have done analysis of different multipulse converters namely twelve pulse ac input current waveform PFC-HMPR, twenty pulse ac input current waveform PFC-HMPR and sinusoidal pulse ac input current waveform PFC-HMPR. The simulated results of 2.2kW model presented here. Further more it's supporting analytical calculations. It is found that as we are approaching near to sinusoidal source current (less THD) efficiency is decreasing (due to increase in switching losses) and complexity of control circuit is increasing. Hence the proposed hybrid rectifier can operate in accordance to the harmonic content restrictions of the input line current with the isolated boost rectifiers processing just the minimum power. Moreover, the economical benefits of this new topology are extremely valuable for high power installations because around 33% maximum value of rated power will be processed in the parallel circuits, in order to reduce the THD_I to a very low value (around 5%). Moreover, when used in retrofitting applications, the available total rated power will increase to 133% of the original output power, with obvious improvements on power quality.

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Appendix
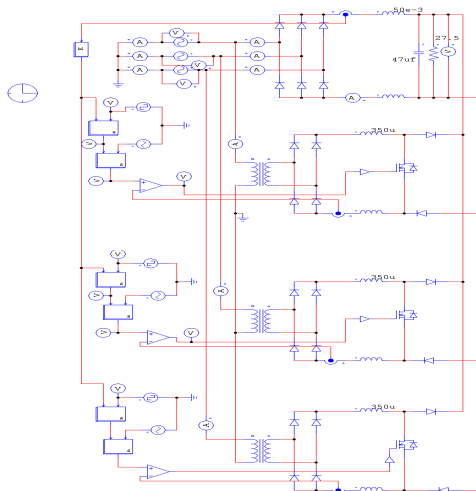**Simulation schematics**

Fig. 19 Psim schematic diagram of isolated boost Twelve pulse HMPR
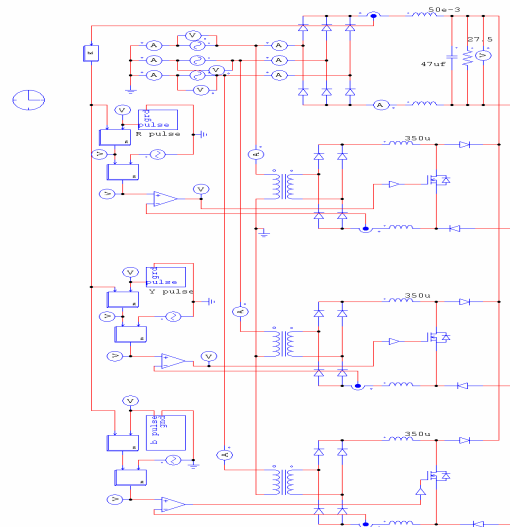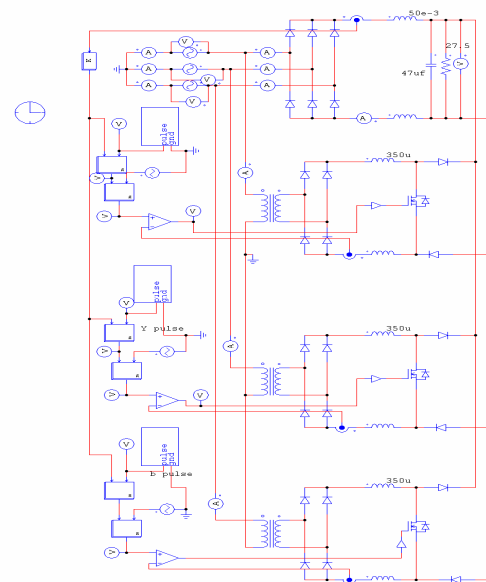

Fig. 20 Psim schematic diagram of twenty pulse HMPR

Fig. 21 Psim schematic diagram of sinusoidal source current