NEW GENERATION THREE-PHASE RECTIFIER

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Abstract: This paper describes an investigation into the development of a new generation of three-phase rectifier, used to power telecommunications equipment. Traditionally, the topology used is a single-phase two-stage design, with a boost converter at the input to the first stage and an isolated dc-dc converter making up the second stage. The boost converter provides power factor correction which is necessary in order to comply with the IEC1000-3-2 standard. The dc-dc stage provides isolation, as well as the fast feedback necessary to regulate the output voltage ripple. This is necessary in order to comply with the psophometric noise standard ITU-T0.41. A two-stage design however, results in a cascade effect contributing to the total power losses. A new rectifier is introduced that can satisfy the required telecommunication industry standards, whilst also having only a single-stage design. This paper discusses the principles of operation and the performance characteristics of the new generation three-phase rectifier.

Key words: three-phase, new generation, telecommunication, rectifier.

1. INTRODUCTION

Traditional rectifiers used in the telecommunications industry are typically a single-phase two-stage design. The reason for a two-stage design is that there are industry specific standards that the rectifiers have to comply with. The major two being the ITU-T0.41 and the IEC1000-3-2 standard [1]. The ITU-T0.41commonly known as the psophometric noise standard was originally introduced to regulate the amount of audible noise on telephone networks. The source of this noise was due to the use at that time of full bridge SCR rectifiers. These rectifiers typically had no output filtering and as a result had considerable noise on the output. The telephone networks were initially analogue and because of the output voltage ripple, audible noise was produced on the phone lines. Nowadays, with digital exchanges the telephone systems have become more immune to dc power supply noise. The psophometric standard is still used however as the defining standard for the interface between telecommunication switching equipment and telecommunication dc power equipment, hence, dc power manufacturers have to comply with this standard in order to market their products.

The IEC1000-3-2 standard was introduced to regulate harmonic currents drawn from the mains supply. These harmonic currents reduce the efficiency of the power drawn from the mains and can excite resonances, as well as overloading the circuit wiring and transformers. Having to comply with these standards has dictated the way in which telecommunications manufacturers have had to design their systems.

A typical telecommunications rectifier is a single-phase two-stage topology as shown in Figure 1. The first stage of the rectifier is usually a boost stage, used to provide power factor correction (PFC) and hence regulate the maximum allowable input harmonic current content defined by the IEC1000-3-2 standard. The boost converter is a popular choice for PFC; this is due to it having a simple topology with a high efficiency. A boost converter however, has an inherent weakness in that it cannot provide effective protection from output short-circuit failure nor high input startup currents [2].

The dc-dc converter second stage is required to provide fast regulation of the output voltage to reject the psophometric noise, as well as provide isolation and voltage transformation. The isolation is both a functional and a safety requirement of the telecommunications industry, whilst the voltage transformation is needed, as telecommunication systems typically operate off a 48V DC supply.

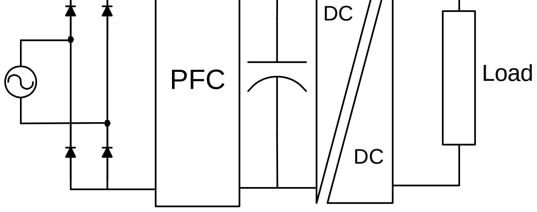

Figure 1: Traditional rectifier.

The traditional single-phase rectifier has at the output of the PFC stage a second harmonic ripple component due to the mains discontinuity at the zero crossing. As a consequence of this, a large storage capacitor is required. Having a two-stage design results in the output power being processed twice, this cascade effect results in a reduction in the overall efficiency. It is well known in the industry that two-stage designs have efficiencies around 90%. Also, a two-stage design requires two independent controllers, one for each stage.

2. ENERGY TRANSFER MODEL

As the traditional two-stage rectifiers have a power factor corrected input, the load appears as being purely resistive. Thus, from a power transfer point of view, the rectifier's input oscillates at twice the mains frequency, and in a single-phase system, because there can be no natural power transfer from the source to load at the mains voltage zero crossing, an energy storage medium (normally a capacitor) is always required to provide a constant transfer of power to the load. The total dc power delivered to the load can only ever be half the peak input power as illustrated in Figure 2. The area under the DC power line of the positive half line cycle constitutes 68% of the input power, while the area above the DC power line consists of the remaining 32% of the input power. This 32% excess power is stored in the capacitor and then used later in each cycle, when the input power drops below the required output power.

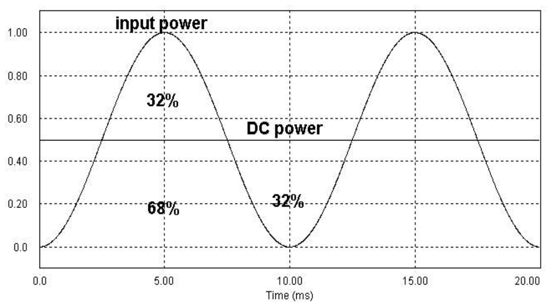

Figure 2: Single-phase normalized power transfer.

In an ideal three-phase system there is a continuous energy transfer from source to load and the total power transferred is the sum of the power from the three individual phases. For a three-phase system with resistive phase loads the power drawn by each phase is given by the following formula:

$$P = \frac{V_p^{\,2} \sin^2 \theta}{R} \quad \text{where } V_p = \text{peak input voltage}$$

Assuming that the voltage is unchanging

$$\frac{V_p^{\,2}}{R} = k \quad \text{where k is a constant}$$

$$\therefore P = k \sin^2 \theta$$

The total power transfer P_{total} for a three-phase system assuming that the voltage is unchanging and R is fixed is given as

$$P_{total} = k\sin^2\theta + k\sin^2(\theta + 120^\circ) + k\sin^2(\theta + 240^\circ)$$

$$= \frac{k}{2}\left[3 - \cos 2\theta - \cos(2\theta + 240^\circ) - \cos(2\theta + 480^\circ)\right]$$

$$= \frac{k}{2}\left[3 - \cos 2\theta + \frac{1}{2}\cos 2\theta - \frac{\sqrt{3}}{2}\sin 2\theta + \frac{1}{2}\cos 2\theta + \frac{\sqrt{3}}{2}\sin 2\theta\right]$$

$$= \frac{3}{2}k$$

It can be seen that the total power drawn by a three-phase system is constant and equal to 1½ times the peak input per phase power as illustrated in Figure 3.

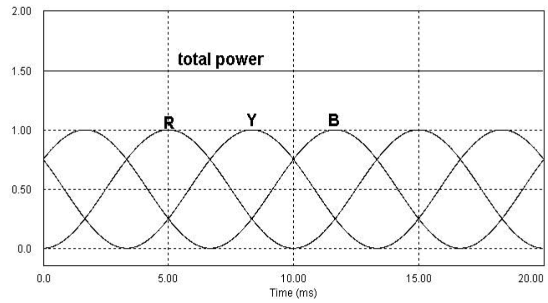

Figure 3: Three-phase normalized power transfer.

A three-phase system has greater supply integrity over a single-phase system, as a single-phase system requires additional phase-neutral protection and is more susceptible to imbalances and harmonics. The availability of a neutral is also known to be an issue in many installations.

3. THREE-PHASE TOPOLOGIES

A number of three-phase topologies exist that could be realized as telecommunication power supplies, with each having its own advantages and drawbacks. However, there are only two single-stage three-phase converters worth mentioning. The first is the Vienna Rectifier which is a three-switch boost-derived rectifier (Figure 4). This rectifier operates by having the input stage creating a dc voltage across the two switches connected to the transformer primary. These two switches, in turn, regulate the voltage being applied to the primary of the transformer and hence control the output voltage [3]. The Vienna Rectifier, even though it operates with only three switches endures higher stresses than that of a six-switch converter (Figure 5). Also, having fewer active switches results in less freedom when it comes to how they can be controlled to produce sinusoidal input currents [4]. The efficiency obtained from this rectifier is around 93%.

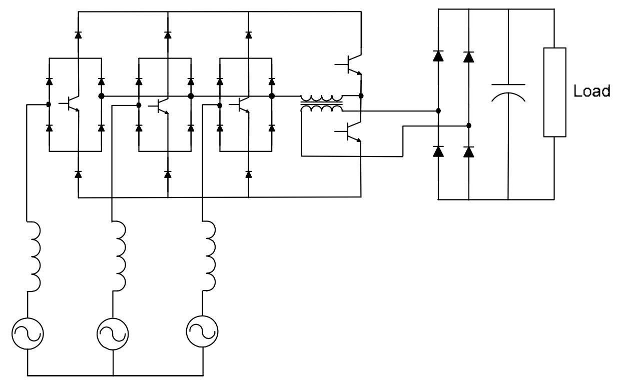

Figure 4: Vienna rectifier.

The second is the six-switch buck converter shown in Figure 5. This type of converter directly converts the three-phase ac to dc in a single isolated buck-derived stage by splitting the conversion process into a three-phase cyclo-converter section. This is then used to synthesise the high frequency ac voltage from the three-phase input voltages. The secondary ac signal is rectified and filtered to obtain the desired output dc voltage. The switching sequence of this type of converter can be implemented by either a look-up table or by an analogue derived PWM circuit. This type of converter can be implemented as a hard switched [5] or soft switched type [6][7]. This topology however, has the disadvantage of requiring ac switches and a complex control strategy. An efficiency of 92% has been documented [8], a comparative performance analysis to existing three-phase topologies can be found in [9].

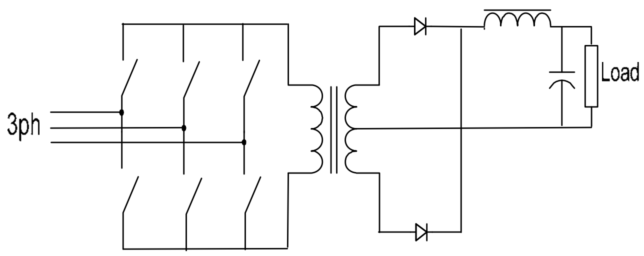

Figure 5: Six-switch buck converter.

A rectifier solution is sought that meets with all the requirements of the telecommunications industry, while not displaying the weaknesses associated with a boost-derived topology and which can be realized with a relatively simple control.

4. NEW RECTIFIER TOPOLOGY

A new three-phase topology is proposed that capitalizes on the ability of a three-phase source to deliver constant power. The topology uses three single-stage converters, with each converter connected across a single phase and controlled to perform a squaring function on the input voltage. Accordingly, this results in a second harmonic voltage waveform, which has the same profile as the natural power transferred to a resistive load.
The rectifier prototype takes the form of a zero voltage switched (ZVS) full bridge converter with a current doubler output topology as shown in Figure 6.

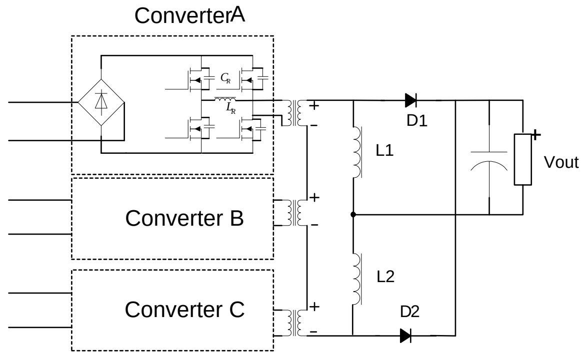

Figure 6: New rectifier topology.

The concept can be modelled by considering each converter A,B,C as an ideal transformer performing a 1:V_{in} transfer function on the input voltage (see Figure 7). Consequently, this results in a squaring action on the input voltages taking place; as a result, the secondary voltages have a power waveform profile which sums to a constant, due to the series connection of the transformer secondaries. If the load is considered resistive, the output current is also constant and unity power factor results. Since V_{in} varies over the range 0 to V_p, with V_p the peak input phase voltage, then accordingly, this converter can be best realized by using a buck-derived topology.

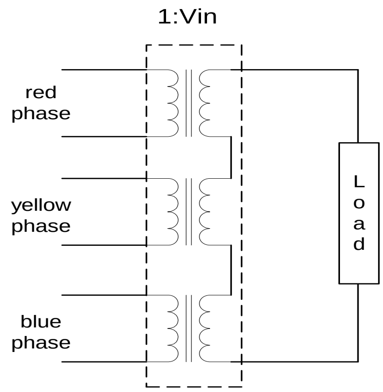

Figure 7: Concept topology model.

Ideally, the new converter system will have the following characteristics:

- Unity input power factor
- Zero output voltage ripple
- Single stage converter
- High output bandwidth
- Isolation
- Voltage transformation

The new rectifier constitutes an isolated topology, necessary for compliance with telecommunication functional and safety requirements. This topology offers high modularity and provides mains balancing, giving the possibility to deliver full output power in case of mains voltage imbalances, whilst using only a single controller. A unity power factor will satisfy the IEC1000-3-2 standard, and with theoretical zero output voltage ripple, compliance with the psophometric standard is guaranteed.

5. SIMULATIONS

The rectifier prototype is simulated using a package called PSIM. The system model is shown in Figure 8 consisting of a balanced three-phase 50Hz input voltage with unity magnitude. Three control blocks, each perform the V_{in}^2 transfer function on the input voltages, with the outputs connected in series to a resistive load.

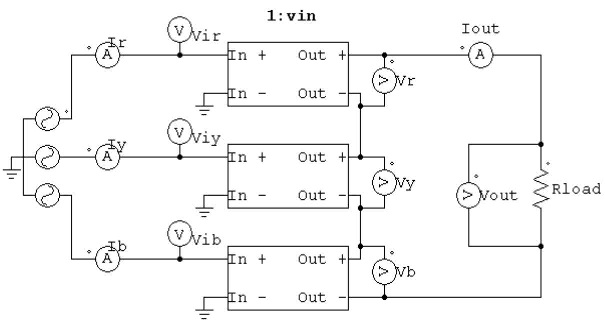

Figure 8: Prototype simulation model.

Figure 9 shows the result of the simulation, with the red phase voltage and current inputs being in phase. Figure 10 shows the three output phase voltages V_r V_y and V_b summing together to form V_{out}. As can be seen, the output voltage and therefore output current are constant, with the output voltage being 1½ times the peak input phase voltage. The results of this simulation show that the proposed topology can theoretically produce zero output voltage ripple and a unity power factor.

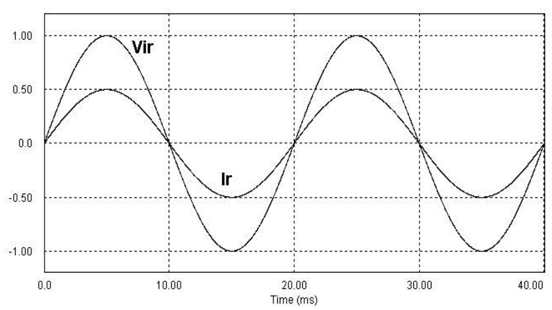

Figure 9: Input phase voltage and current.

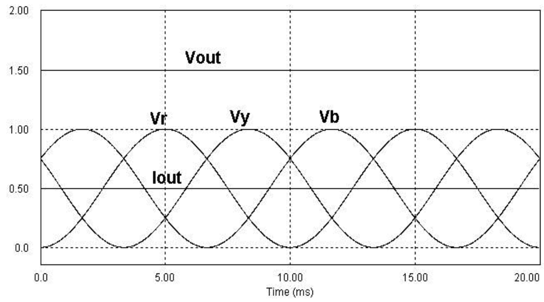

Figure 10: Output waveforms.

6. RECTIFIER OPERATION

A three-phase 500W rectifier prototype using three single-phase full bridge modules, each connected to a phase voltage in a star connected system was constructed. The three modules have their output transformers connected together in series, feeding into a current doubler topology (see Figure 6).

The rectifier prototype was controlled using a TMS320F2812 digital signal processor (DSP) which operated at a switching frequency of 100kHZ. The system used a three-phase phase locked loop (PLL) in order to synchronise the V_{in}^2 switching envelope with the mains voltages. The PLL algorithm was embedded in the DSP. Three PWM output waveforms from the DSP each control a converter module. Each converter module is controlled by switching the left and right leg of the full bridge at a constant 50% duty cycle and phase shifting between them to produce the desired output voltage. The phase shifting was achieved by the use of a GAL26CV12 programmable logic device.

7. RESULTS

The converter prototype was tested in order to evaluate its performance against the telecommunication industry standards.

It was found that at full load the rectifier prototype produced an input current with a THD=11.9% and PF=0.99 as shown in Figure 11.

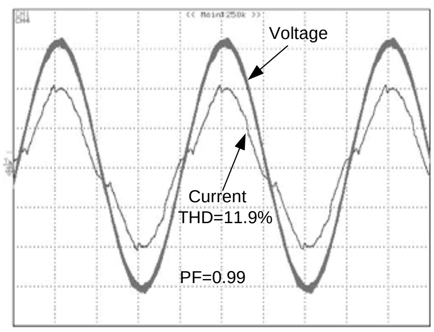

Figure 11: Phase voltage and current.

This is consistent with the simulated waveforms showing a unity PF, however, with a current THD=11.9% the maximum power rating that the rectifier would be able to operate up to would be 6.5kW as above this level the harmonic current magnitudes would exceed the limits stipulated in the IEC1000-3-2 standard. The current THD value can be further reduced by connecting the supply in a delta configuration and in so doing eliminating the dominant third harmonic component present in the neutral. This would therefore increase the operating power range of the rectifier while still complying with the IEC1000-3-2 harmonic limits.

It was not possible to test the system against the psophometric noise standard, which dictates that the output voltage ripple not exceed $2mV_{rms}$. This was due to the prototyping nature of the rectifier which did not have the necessary output filtering nor the high bandwidth closed loop control necessary for the tight output voltage regulation. The system was therefore run under open loop control.

It was found that under full load the output voltage waveform exhibited a second harmonic component with a magnitude of $1.48V_{rms}$. This is due to slight imbalances in the power transferred between the three converter modules (Figure 12).

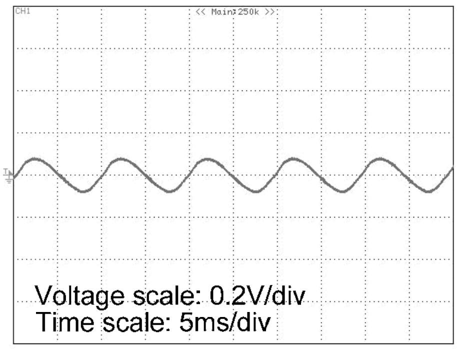

Figure 12: Output voltage ripple.

It is the authors' opinion that with the correct output filtering and high speed feedback loops in place, the rectifier would be able to comply with the psophometric standard necessary for any commercial telecommunications power converter.

The efficiency is examined in order to determine whether there is a clear advantage over existing two-stage topologies. Typical efficiencies reached by two-stage topologies are around 90%, with each stage having around 5% losses (i.e. 95% efficiency) [10]. The rectifier efficiency curve is shown in Figure 13. The maximum efficiency of 89.3% occurs at 489W of output power. It was found that the majority of the losses (25%) originated in the output diodes as a result of conduction losses due to the high on-state voltage. This loss can be reduced by using silicon schottky diodes which have a reduced on-state voltage compared with the ultra fast diodes used. The MOSFETs constituted the second highest loss (23%) as a result of having six of them being on at any time. These losses are conduction losses only since with ZVS there are no switching losses. These conduction losses can be reduced by using MOSFETs with lower R_{ds} values.

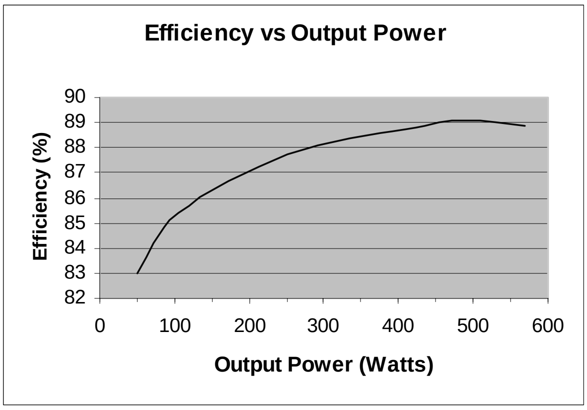

Figure 13: Efficiency vs output power.

8. CONCLUSION

As a result of the tests performed on the three-phase rectifier prototype is was found that the rectifier would meet with the IEC1000-3-2 standard up to 6.5kW. This power range could be extended by improving the current THD level by running the system on a delta connected supply and in so doing reducing the third harmonic current component which is present in the neutral that connects all three modules together. Testing the system against the psophometric noise standard was not possible due to the rectifier being at the prototype stage. This is something that can only be authenticated through future research work. The efficiency of the rectifier prototype was found to be approximately 89%, with current commercial three-phase topologies discussed in section 3 obtaining efficiencies around 93%. It was identified that the majority of the losses were conduction losses which could be reduced through componentry changes. Therefore, it is believed that future upgrades of the rectifier topology will result in efficiencies matching or possibly exceeding current commercial three-phase telecommunication rectifier models. All this can be achieved by using relatively simple control strategies, reducing the cost of the overall solution.

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