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A New Interleaved Three-Phase Single-Stage PFC AC-DC Converter with Flying Capacitor

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Abstract: A new interleaved three-phase PFC AC-DC single stage multilevel is proposed in this paper. The proposed converter uses a flying capacitor structure with a standard phase shift PWM to improve efficiency, particularly at light load conditions. In the paper, the operation and its steady state characteristics are explained and its design is discussed. The feasibility of the new converter is confirmed with experimental results obtained from a prototype converter. The proposed converter integrates the operation of the boost power factor correction and the three-level dc–dc converter. The converter is made to operate with two independent controllers—an input controller that performs power factor correction and regulates the dc bus and an output controller that regulates the output voltage. The input controller prevents the dcbus voltage from becoming excessive while still allowing a single-stage converter topology to be used. The paper explains the operation of the new converter in detail and discusses its features and a procedure for its proper design.

Keywords: AC–DC Power Conversion, Three-Stage Power Factor Correction, static induction thyristor, single-stage power factor, Flying Capacitor.

I INTRODUCTION

The concept of interleaving, or more generally that of increasing the effective pulse frequency of any periodic power source by synchronizing several smaller sources and operating them with relative phase shifts. Interleaving technique actually exists in different areas of modern technologies in different forms. Take a typical automobile engine as an example. In today's internal combustion engine, several cylinders are connected to a common crankshaft and that the power stroke portions of their cycles are non-simultaneous. By firing each cylinder in sequence, the effective pulse frequency of the engine is increased and the net torque ripple is reduced. Increasing the number of cylinders raises the pulse frequency and total output power of the engine without increasing the firing frequency of the individual cylinders. This could be considered as a very good example of interleaving technique being applied in the field of mechanical engineering.

In the field of power electronics, application of interleaving technique can be traced back to very early days, especially in high power applications. In high power applications, the voltage and current stress can easily go beyond the range that one power device can handle. Multiple power devices connected in parallel and/or series could be one solution. However, voltage sharing and/or current sharing are still the concerns. Instead of paralleling power devices, paralleling power converters is another solution which could be more beneficial. Furthermore, with the power converter paralleling architecture, interleaving technique comes naturally. Benefits like harmonic cancellation, better efficiency, better thermal performance, and high power density can be obtained. In earlier days, for high power applications, in order to meet certain system requirement, interleaving multi-channel converter could be a superior solution especially considering the available power devices with limited performance at that time. One of such example can be found in the application of Superconducting a Magnetic Energy Storage System (SMES) [2]. The current stress of such application is extremely high, yet certain system performance still need to be met. On the ac side, the total harmonic distortion (THD) in voltages and currents of the regulatory standards must be respected. A further constraint comes from the switching loss that is proportional to the valve switching frequency. The proposed solution in the referred paper consists of using multiple interleaved three-phase current-source converters. With this multi modular converters the current stress can be divided to a level that can be handled by gate turn-off thyristor (GTO), the static induction thyristor (SI), etc, and reduces the ohmic component of their conduction losses. The results shows interleaving technique was applied quite successful in this application. Such examples also can be found in many other applications, such as Static VAR Generator (SVG), high voltage direct current (HVDC) applications etc.

Interleaving technique was also investigated in the early days for the smaller power spacecraft, satellite or avionic applications, and was introduced as unconventional SMPS power stage architecture [5]. In such applications, one major concern is the input and output filters rely almost exclusively on tantalum capacitors due to the highest available energy-storage-to-volume ratio at that time. However, the ESR of this filter capacitor causes high level thermal stress from the high switching pulsed current. The input and output filter capacitance is usually determined by the required

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number of capacitors sufficient to handle the dissipation losses due to the ripple current. Interleaving multiple converters can significantly reduce the switching pulsed current go through the filter capacitor.

The ESR of the tantalum capacitors is inversely proportional to the frequency. Interleaving technique can effectively reduce the filter capacitor size and weight. Another concern of this application is packaging. Due to the thermal management issues, the power loss of non-interleaved converter exceeds the typical dissipation capability of a slot mount circuit packaing card. In addition, the substantial bulky converter usually requires a custom designed mainframe. With the interleaving architecture, increased output power may be supplied by adding additional identical modules. The interleaved converter was designed and developed which can well demonstrate the benefits on input/output filter, packaging, and modularity.

II LITERATURE SURVEY

Flying Capacitor multilevel inverters:
As we know that a multilevel inverter is an electrical device that converts a DC power supply into an AC power supply. Multilevel inverter converts number of DC supplies into AC supply. The DC source can come from anywhere like solar energy or wind energy.

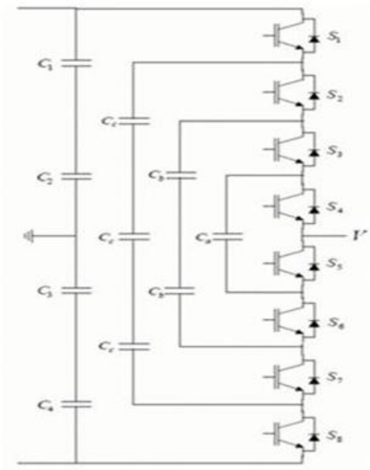

Fig: Flying Capacitor multilevel inverters

AC-DC Converters:
One of the first and most widely used application of power electronic devices have been in rectification. Rectification refers to the process of converting an ac voltage or current source to dc voltage and current. Rectifiers specially refer to power electronic converters where the electrical power flows from the ac side to the dc side. In many situations the same converter circuit may carry electrical power from the dc side to the ac side where upon they are referred to as inverters. In this lesson and subsequent ones the working principle and analysis of several commonly used rectifier circuits supplying different types of loads (resistive, inductive, capacitive, back emf type) will be presented.

• Waveforms and characteristic values (average, RMS etc) of the rectified voltage and current.
• Influence of the load type on the rectified voltage and current.
• Harmonic content in the output.
• Voltage and current ratings of the power electronic devices used in the rectifier circuit.
• Reaction of the rectifier circuit upon the ac network, reactive power requirement, power factor, harmonics etc.
• Rectifier control aspects (for controlled rectifiers only) In the analysis, following simplifying assumptions will be made.
• The internal impedance of the ac source is zero.
• Power electronic devices used in the rectifier are ideal switches.

The first assumption will be relaxed in a latter module. However, unless specified otherwise, the second assumption will remain in force. Rectifiers are used in a large variety of configurations and a method of classifying them into certain categories (based on common characteristics) will certainly help one to gain significant insight into their operation. Unfortunately, no consensus exists among experts regarding the criteria to be used for such classification.

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Half-Wave Rectifier:
In half-wave rectifier, half of the ac cycle pass, while during the other half cycle the diode blocks the current from flowing. Basic half-wave rectifier circuit may be constructed with a single diode in a one phase supply, or three diodes with a three-phase supply. Such circuits are known as half wave rectifier as they only work on half of the incoming ac wave.

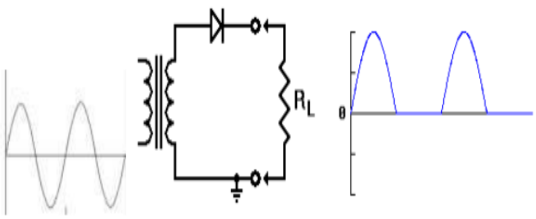

Figure: Half Wave Rectifier

Full-Wave Rectifier:
A full-wave rectifier converts the whole incoming ac wave so that both halves are used to cause the output current to flow in same direction (either positive or negative). Full-wave rectification is more efficient because it converts both polarities of input waveform to DC. A full-wave rectifier circuit requires four diodes instead of one needed for half-wave rectification. For the arrangement of four diodes the circuit is called a diode bridge or bridge rectifier.

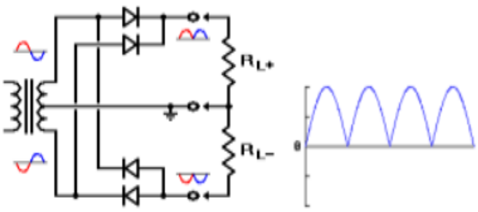

Figure: Full Wave Rectifier

Three Phases Half Wave Rectifier:
The operation theory is like a single phase half wave rectifier. As each of the phases reach 0.7V the diode of the respective phase start conducting. The resultant current flows through the load.

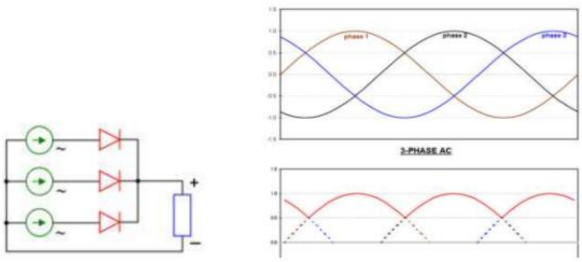

Figure: phase half wave rectifier

3-Phase Full Wave Converter:

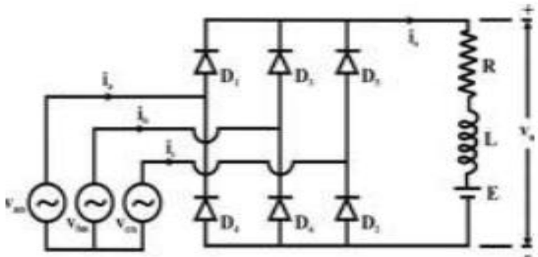

Figure: phase full wave rectifier

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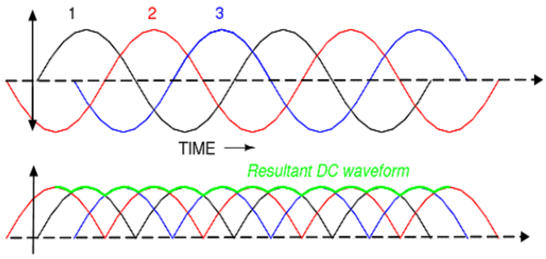

Figure: Input and output voltage waveform for 3 phase full wave rectifier

Active Power Factor Correction:

Active PFC can be implemented by controlling the conduction time of the converter switches to force the ac current to follow the waveform of the applied ac voltage. There are two-stage and single-stage power factor correction techniques. These techniques are discussed below.

Two-stage power factor correction:

Two-stage PFC using an input current shaper followed by a dc/dc converter is the fundamental approach for active PFC. A block diagram of this technique is shown in figure 2.6. The power factor pre-regulator allows the rectifier to draw current from the supply during the whole power cycle, instead of the current pulses drawn by the traditional diode rectifier, and this current is made to follow a sinusoidal reference in phase with the supply voltage [13-15]. The most widely used pre-regulator circuit is the boost converter and it can be operated either in discontinuous conduction mode (DCM) in the voltage mode control or in continuous conduction mode (CCM) in the current mode control. Buck and buck-boost converters can also be used as input current shapers but some distortion must be allowed in the case of buck converters; whereas efficiency is degraded and component stresses are high in the case of buck-boost converters. The boost converter provides superior performance at the expense of the necessity of having the output voltage higher than the peak input voltage. Pulse width modulation (PWM) is most commonly used to achieve those two tasks. Several control methods can be used for input current shaping, such as average current mode control, peak current mode control or hysterisis control and nonlinear carrier control. The dc/dc converter stage can be a forward, a fly back or any other step down converter.

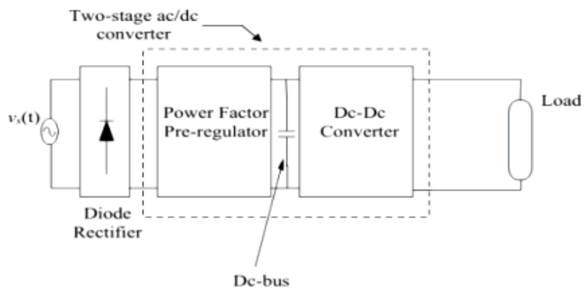

Figure: Block diagram of standard two-stage PFC ac/dc converter

Other methods for two-stage PFC include the use of active shunt regulators and active power filters. The objective is to reduce the percentage of power processed by the additional stage to increase the conversion efficiency. In the case of shunt regulators, they are connected at the input of the dc/dc converter or directly to the output to supply part of the required energy.

Single-stage power factor correction:

Since regulatory agencies on the power factor, do not require a perfectly sinusoidal input line current, efforts have been made to obtain smaller converters with fewer switches that could comply with the regulations and be more cost effective. This led to the emergence of single-stage power factor corrected (SSPFC) converters. SSPFC circuits are required to provide the features of both the power factor pre regulators in addition to those of the dc/dc converter cascaded with it. These features are:

i. A well regulated output voltage.
ii. Isolation between the input ac mains and the output load on the dc side.
iii. A sinusoidal input line current with low harmonic distortion that meets the requirements of IEC 100-3-2 and IEC 1000-3-4 standards.

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iv. High efficiency by eliminating/reducing switching and conduction losses.
v. Small component sizes and reasonable voltage and current ratings.

The basic SSPFC circuits were introduced in the early 1990s by Madigan et. al. This was achieved by integrating the boost input current shaping converter with either a fly back or a forward converter [35].

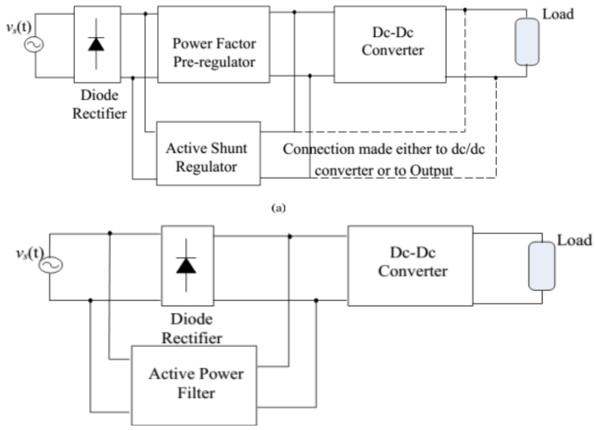

Figure: Other two-stage PFC techniques (a) Active shunt regulator (b) Active power filter

This capacitor voltage can reach very high levels especially at light load conditions. This imposes a high voltage stress on the converter switches. Many attempts have been made to reduce this voltage stress by using output or dc-bus voltage feedback as was presented in [42, 43]. But the main limitation of the SSPFC topologies is on the practical power processing capability.

III IMPLEMENTATION

Most three-phase single-stage converters operate with discontinuous input currents. As a result, semiconductor current stresses are increased and there is a need to implement the converters with a large input filter to filter out large high-frequency harmonics [11]-[12], [15], [16],[20]-[23]. A three-phase, single-stage three-level converter proposed in [23] mitigates these drawbacks. Although the converter proposed in that project was an advance over previously proposed three-phase single-stage converters, it still suffered from the need to have a discontinuous output inductor current at light load conditions to keep the DC bus capacitor voltage less than 450V and it needed to operate with discontinuous input current, which resulted in high component current stress and the need for significant input filtering due to the large amount of ripple.

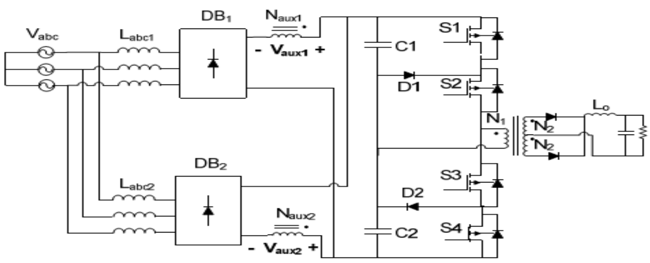

Fig: An interleaved three-phase three-level converter

The topology proposed in [24] and shown in Fig is an interleaved three-phase, single-stage rectifier that has an output current that is continuous for all load ranges, a dc bus voltage that is less than 450 for all load conditions, and superior input current harmonic content. The PWM method that is needed to operate the converter is shown in Fig 3.2. As can be seen, this PWM method is not standard phase-shift PWM (PWM) and is therefore not found in commercially available integrated circuits (ICs). Moreover, this converter cannot operate with soft-switching except under heavy load conditions. A new interleaved three-phase single-stage PFC AC-DC that can operate with standard phase-shift PWM and with soft switching over a wider load range is proposed in this project. In this project, the operation of the converter and its steady-state characteristics are explained and its design is discussed. The feasibility of the new converter is confirmed with experimental results obtained from a prototype converter.

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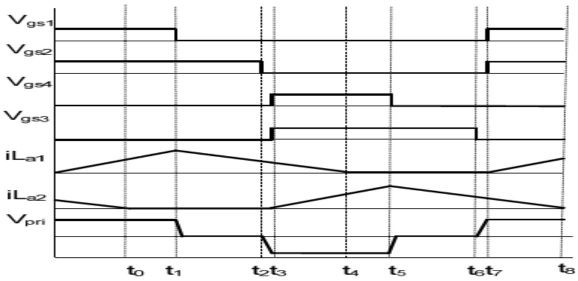

Fig: Typical waveforms describing the modes of operation.

Phase-Shift Modulated PWM Technique:

The converter and its key waveforms are shown in below figure.

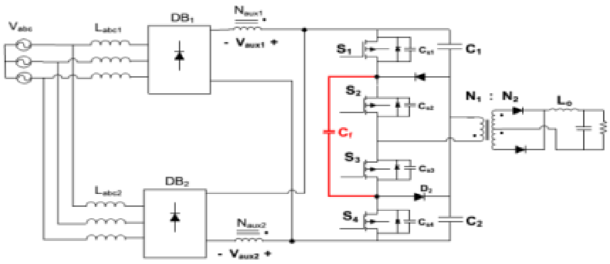

Fig: Proposed single-stage three-level AC-DC converter

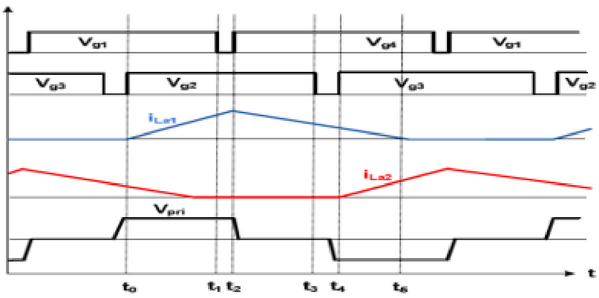

Fig: Typical waveforms for proposed converter

The proposed converter uses auxiliary windings that are taken from the converter transformer to act as "magnetic switches" to cancel the dc bus capacitor voltage so that the voltage that appears across the diode bridge output is zero. When the primary voltage of the main transformer is positive, Auxiliary Winding 1 (Naux1/N1=2) cancels out the dc bus voltage so that the output voltage of Diode Bridge 1 (DB1) is zero and the currents in input inductors La1, Lb1, and Lc1rise. When the primary voltage of the main transformer is negative, Auxiliary Winding 2 (Naux2/N1=2) cancels out the dc bus voltage so that the output voltage of Diode Bridge 2 (DB2) is zero and the currents in input inductors La2, Lb2, and Lc2 rise When there is no voltage across the main transformer primary winding, the total voltage across the dc bus capacitors appears at the output of the diode bridges and the input currents falls since this voltage is greater than the input voltage. The converter has the following modes of operation during a half switching cycle and equivalent circuit diagrams that show the converter’s modes of operation are shown in Figure.

Mode 1 (t0< t < t1):

During this interval, switches S1and S2are ON. In this mode, energy from dc bus capacitor C1flows to the output load. Due to magnetic coupling, a voltage appears across Auxiliary Winding 1 that is equal to the dc bus voltage but with opposite polarity cancels the total dc bus capacitor voltage. As a result, the voltage at the diode bridge output is zero and the input currents in La1, Lb1, and Lc1 rise.

Mode 2 (t1< t < t2):

In this mode, S1is OFF and S2 remain ON. Capacitor Cs1charges and capacitor CS4 discharges through Cf until Cs4, the output capacitance of S4, is fully discharged. The energy stored in the input inductor during the previous mode starts being transferred into the dc-link capacitors. This mode ends when S4turns on with zero-voltage switching (ZVS).

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Mode 3 (t2< t < t3):
In Mode 3, S1is OFF and S2 remain ON. The energy stored in the input inductor L1during Mode 1 is transferred into the dc-link capacitors. The voltage that appears across Auxiliary Winding 1 is zero. The primary current of the main transformer circulates through D1and S2. With respect to the converter's output section, the load inductor current freewheels in the secondary of the transformer, which defines a voltage across the load filter inductor that is equal to –VL.

Mode 4 (t3< t < t4):
In this mode, S1 and S2 are OFF. The energy stored in L1continues to be transferred into the dc bus capacitor. The primary current of the transformer discharges the output capacitance Cs3 and also charges C2 through the body diodes of S3and S4. Switch S3 is switched ON at the end of this mode.

Mode 5(t4< t < t5):
In this mode, S3and S4are ON and energy flows from capacitor C2into the load. A voltage appears across Auxiliary Winding 2 that is equal to the dc bus voltage so that the winding acts like a magnetic switch and cancels out the voltage. The voltage across the boost inductors L2 (L2= Labc2) becomes the rectified supply voltage of each phase and the current flowing through each inductor increases. This mode ends when the energy stored in L1is completely transferred into the dc bus capacitors. For the remainder of the switching cycle, the converter goes through Modes 1 to 5, but with S3 and S4ON instead of S1and S2and DB2conducting current instead of DB1.

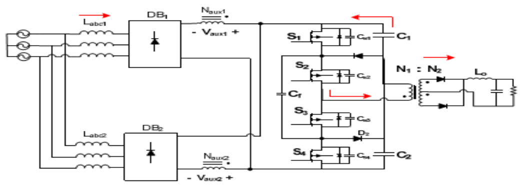
Mode 6:
In this mode, S3and S4are ON and a symmetrical period begin. Energy flows from capacitor C2 into the load. The voltage across the boost inductors L2becomes only the rectified supply voltage of each phase and the current flowing through each inductor increases.

Mode 7:
In this mode, S3 is ON and S4is OFF. Capacitor Cs3 charges and capacitor Cs1discharges through Cf until Cs1, the output capacitance of S1, is completely discharged. The energy stored in the input inductor during the previous mode begins to be transferred into the dc-link capacitors. This mode ends when S1 turns on with ZVS.

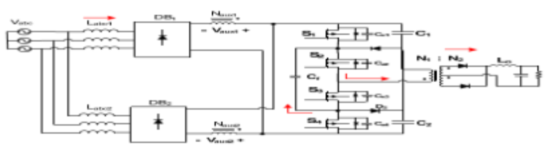
Mode 8:
In this mode, S3is ON and S4is OFF and the primary current of the main transformer circulates through diode D2 and switch S3. The energy stored in the boost inductors L2 during the previous mode starts being transferred into the dc bus capacitor.

Mode 9:
In this mode, S3and S4are OFF and the primary current of the transformer charges capacitor C1 through the body diodes of S1 and S2. The energy stored in the boost inductors L2 is also transferred into the dc bus capacitor.

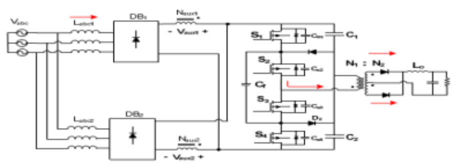
Mode 10:
In this mode, S1and S2are ON and energy from dc bus capacitor C1flows to the output load. This mode ends when the energy in inductors L2 is completely transferred into the dc bus. The switching cycle ends at time t8and another switching cycle having the same modes of operation begins.



Mode 1 (t0< t < t1)



Mode 2 (t1< t < t2)



Mode 3 (t2< t < t3)

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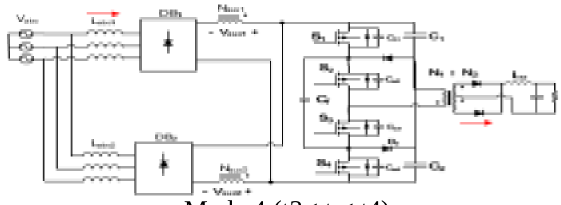
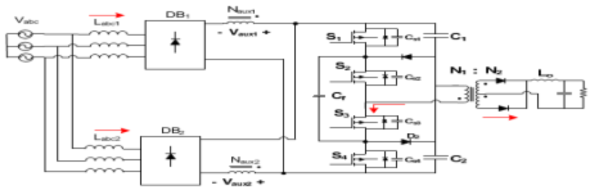


Mode 4 (t3< t < t4)



Mode 5 (t4< t < t5)

Figure: Modes of operation

When trying to design the proposed converters are discussed in this section of the project. The key parameters values in the design of the converter are output inductor Lo, transformer turns ratio N and input inductor Lin. The following should be considered when trying to select values for these components:

Transformer turns ratio N:

The value of N affects the primary-side dc bus voltage. It determines how much reflected load current is available at the transformer primary to discharge the bus capacitors. If N is low, the primary current may be too high and thus the converter will have more conduction losses. If N is very high, the amount of current circulating in primary side is reduced, but the primary current that is available to discharge the dc-link capacitors may be low and thus dc bus voltage may become excessive under certain operating conditions (i.e. high line). The minimum value of N can be found by considering the case when the converter must operate with minimum input line and, thus, minimum primary-side dc bus voltage and maximum duty cycle.

Output inductor Lo:

The output inductor should be designed so that the output current is made to be continuous under most operating conditions, if possible. The minimum value of Lo should be the value of Lo with which the converter's output current will be continuous on the when the converter is operating with maximum input voltage, minimum duty cycle and minimum load. If this condition is met, then the output current will be continuous for all other converter's operating conditions. On the other hand, the value of Lo cannot be too high as the dc bus voltage of the converter may become excessive under very light loads conditions.

Input inductor Lin:

The value for L1 and L2 should below enough to ensure that their currents are fully discontinuous under all operating conditions, but not so low as to result in excessively high peak currents. It should be noted that input current is summation of inductor currents iL1and iL2 which are both discontinuous. However, by selecting appropriate values for L1 (=La1=Lb1=Lc1) and L2 (= La2= Lb2= Lc2) in such a way that two inductor currents such as iLa1and iLa2have to overlap each other, the input current can be made.

IV RESULTS

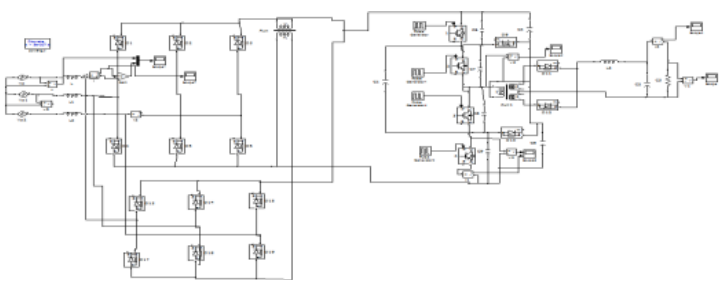


Figure : Typical converter

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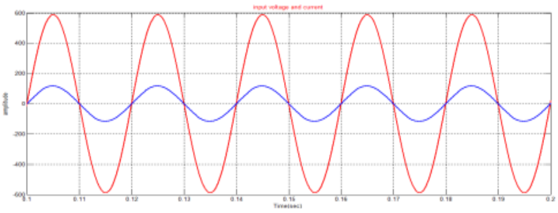

Figure: Wave forms for input current and voltage

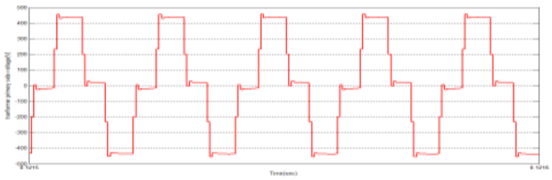

Figure: Primary voltage of the main transformer

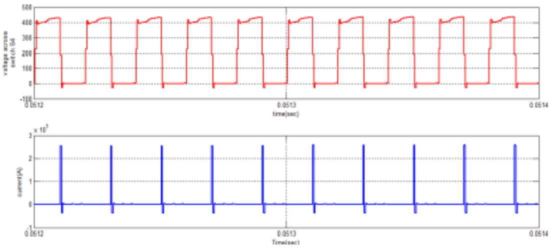

Figure: V_{dc} and I_d current of switch 4

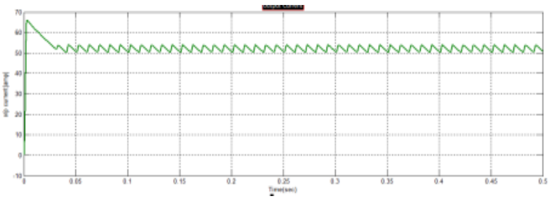

Figure: output current waveform

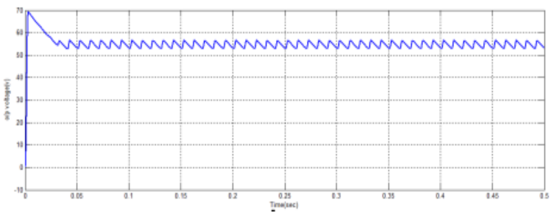

Fig: output voltage wave form

V CONCLUSION

A new three-phase three-level single-stage power-factor corrected ac–dc converter with interleaved input has been proposed in this project. The converter operates with a single controller to regulate the output voltage and uses auxiliary windings taken from its power transformer as magnetic switches to cancel the dc bus voltage so that the input section operates like a boost converter. The proposed converter has the following features.
1) The proposed converter can operate with lower peak voltage stresses across its switches and the dc bus capacitors as it is a three-level converter. This allows for greater flexibility in the design of the converter and ultimately improved performance.
2) The proposed converter can operate with an input current harmonic content that meets the EN61000-3-2 Class A standard with reduced input filter due to the interleaved structure.
3) The output inductor of the proposed converter can be designed to work in continuous conduction mode over a wide range of load variation and input voltage. This results in a lower output inductor current ripple than that found in previously proposed converters which helps reduce secondary component stresses and filtering.

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4) The aforementioned features are all an improvement on the original non interleaved converter that was presented in [24]. Moreover, the proposed interleaved converter operates with greater efficiency than the converter proposed in [24] because it has fewer diodes in the dc bus and it has less turn-on losses.

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