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A Half Power Rating Improved 3-Phase Six-Switch Boost Rectifier Using Two Half Controlled Configurations with a Common DC Bus

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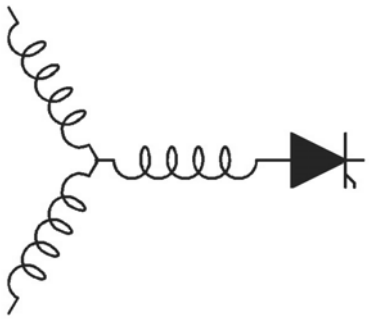

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A half-power rating improved 3-phase six-switch boost rectifier using two half controlled configurations with a common DC bus

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Abstract – **An improved 3-phase isolated controlled rectifier with unity power factor interface and sinusoidal current waveforms is proposed in this paper. The power ratings of the active devices are reduced to half the rated power of the rectifier. The proposed rectifier consists of two complementary isolated half controlled circuits connected to a common DC bus. A 3-phase transformer with one primary and two complementary secondary windings is employed at the AC side for electrical isolation between the source and the load as well as between the two half controlled rectifiers. In addition to functioning as rectifiers, the two complementary circuits act as an active filter for each other in order to eliminate the low order harmonics both in the AC and DC sides. A simple cross-coupled control algorithm has been proposed in order to realize the above scheme. The proposed rectifier is shoot-through safe, requires single power supply for its gate drives and operates with higher efficiency. The higher efficiency is achieved due to lower switching losses since the switches carry only 50% of the rated current. The proposed topology has been studied for future implementation on a 40kW rectifier using SABER and the simulation results are presented. The proposed topology will provide distinct advantages in terms of cost and ruggedness of the system compared to existing regular six switch inverters.**

Keywords: 3-phase half controlled rectifier, complementary isolation transformer, unity power factor interface, half-power rating active devices, active-filter, shoot-through free leg structure.

I. INTRODUCTION

In previous papers [1-3], the potential of the half controlled 3-phase pulse width modulated boost rectifier has been investigated. In the previous papers the major emphasis were either on reduction of cost by using a 3-phase half-controlled circuit [1, 2] or having isolated multiple DC bus for multiple loads [3] employing two complementary half controlled circuits. For an individual half controlled circuit the cost of the system inherently will be reduced since only three active devices are used compared to six devices for its fully controlled counter part. However, the price to be paid was in terms of higher THD and low order even harmonics on both AC and DC side. Thus the system efficiency and performance both becomes degraded.

The overall THD of the system was improved to some extent with a lagging power factor current command [2]. However, appreciable THD still remained which was far from satisfactory given the IEEE 519 standards. Also, lagging power factor command may not suit all rectifier loads. On the contrary, rectifier loads most often demand an unity power factor interface.

Some of these problems such as lower order harmonics from the AC side and DC bus are partially solved by combining two complementary half controlled rectifiers and applying a coordinated central control (CCC) algorithm [3] on them. By this approach the AC side THD was improved markedly, but DC side lower order even harmonics existed. However, the major emphasis in the second paper was to have isolated DC bus for each half-controlled circuit and not much attention was given for reduction of the KVA ratings of the active device or cost of the system. The potential of the complementary circuits connecting to a common DC bus for driving a single load was not explored in those papers.

In this present paper, an attempt has been made to replace a regular 3-phase controlled boost rectifier by a new configuration employing two complementary half controlled circuits sharing a common DC bus. With the proposed new configuration and by employing suitable control algorithm it is possible to reduce the KVA rating of the active devices to as low as 50% of the rated power of the system whereas similar performance of a regular 3-phase full controlled rectifier is achieved.

It is mentioned in earlier paper [3] that a half-controlled circuit can be of two types; common emitter type or common collector types. In the former, since the emitters of the devices are connected to the negative DC bus, they do not require isolated power supply for their gate drives. On the other hand the common collector types require isolated power supply for the same. Again, complementary configuration may be achieved either by using two complementary 3-phase half-controlled circuits or by having a 3-phase isolation transformer with two complementary secondary windings. In this paper the second approach is followed.

Normally in a boost rectifier, inductors are used in series with the phases in order to reduce the amplitude of the switching frequency harmonics of the system. In a 3-phase half controlled circuit, since the phase currents will contain appreciable lower order harmonics [2] the inductors will incur extra losses and also the system will

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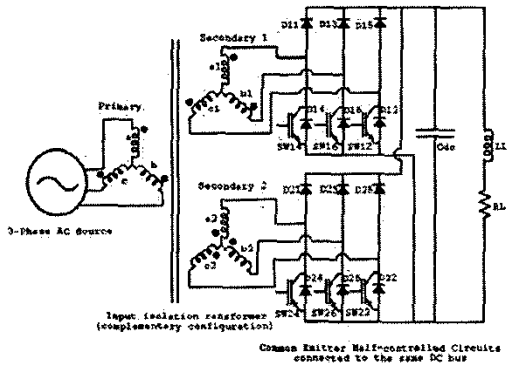

Fig. 1 Proposed half-power rating rectifier with two complementary half controlled circuit connected to a common DC bus

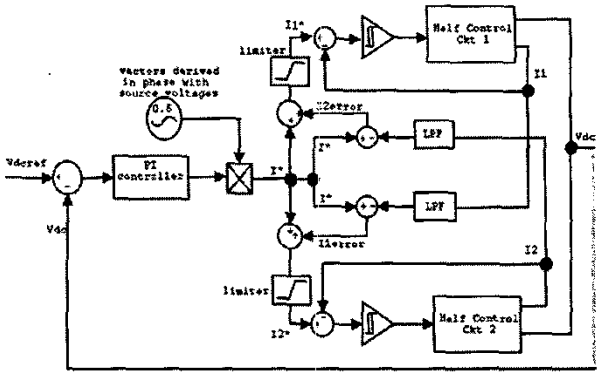

Fig. 2 Control block diagram of the proposed rectifier

be prone to acoustic noise. These may be considered as potential drawbacks for the half-controlled configuration. In case of complementary configuration two separate sets of line inductances are needed. It will be shown in the latter part of this paper that by employing suitable controller a near sinusoidal current waveform may be achieved by combining the currents of two half controlled circuits. In such situations it is advantageous to simply combine the inductors as leakages of the line side isolation transformer. Combining both the secondary windings of the isolation transformers in the same core and their combined current waveform being sinusoidal, the core loss and the core vibrations due to low order harmonics will be nearly eliminated. Thus the proposed transformer configuration will act as an isolator and also serve the additional purposes of elimination of extra losses and acoustic noise of the system.

II. CIRCUIT DESCRIPTION AND POTENTIAL SUPERIORITY OF THE CONFIGURATION

The proposed configuration is shown in Fig. 1. It may be seen that two similar common emitter type half controlled 3-phase rectifiers are connected to the same DC bus with a common RL load. On the AC side, the half controlled circuits are connected to two separate complementary secondary windings of a 3-phase isolation transformer. The line side inductances for the boost rectifier are combined as part of the leakages of the secondary windings of the transformer. The primary side of the transformer is connected to a balanced 3-phase AC source. In each half-controlled 3-phase circuits only three active devices (in this paper IGBTs) are used even though the numbers of diodes used are still six. It may be seen that by combining both the half controlled circuits, total 6 switching devices and 12 diodes are needed for the proposed configuration compared to a regular rectifiers with 6 switches and 6 diodes.

Since the component count of the system has increased, at a first glance it may appear as if it is a disadvantage for the proposed configuration. However, since the two half controlled circuits are connected in parallel to the same load through a common DC bus, the total load will be shared equally by both of them. Hence, for 1 pu (per unit) system load each of them will share only 0.5 pu. Thus all the six active devices will be rated for 0.5 pu power. With such an arrangement the power rating of the switches are reduced by 50% compared to a full bridge controlled rectifier where all the six switches are rated for 1 pu power. Also the rating of the diodes will be reduced to 50% of the rated power of the combined system. Thus it can be inferred that the combined rectifier can be only half the rated power of the system.

The mere combinations of the two half-controlled circuits do not however give satisfactory performance of the system. Even though the performance of the system may improve compared to one half controlled circuit but still it is far from satisfactory [3] and not is comparable to that of a full controlled six switch rectifier. In order to achieve a comparable performance of a regular active rectifier, a simple cross coupled control algorithm is proposed here through which near sinusoidal unity power factor interface with the utility is achieved and also the half power rating of the power devices is maintained. The proposed control algorithm is explained in detail in the subsequent sections.

It is shown in Fig. 1 that by employing complementary configuration in the transformer, both the half controlled circuits are achieved with common emitter switching devices (see Fig. 1). As mentioned in [3], the advantage of this configuration is that none of the half controlled rectifier needs isolated power supply for their gate drives for driving their switching devices. In addition, it may be seen that both the half-controlled circuits are shoot-through protected which is an important advantage of the proposed topology over a regular six switch active rectifiers. Thus, potentially the proposed topology may be considered as rugged and cost-effective compared to the existing controlled rectifiers.

III. CONTROL SCHEME

In this section the control strategy for the complementary configuration with common DC bus control is discussed. Since, both the half control circuit is connected to a common DC bus, only one DC bus voltage sensor is sufficient in contrast to multiple DC bus link application [3] of the same topology. The proposed

control block diagram is given in Fig. 2. In the proposed control scheme the outer loop is regarded as DC bus voltage control loop. A PI controller is used for regulating the DC bus voltage. The output of PI controller decides the amplitude of current through phases. This amplitude when multiplied with sinusoidal unit vectors derived in phase with the phase voltage gives the combined current references for each phase of the primary side of the transformer. However, the reference current for each complementary configuration is half of these combined reference currents. Thus the combined reference currents multiplied by 0.5 gives the reference currents for the phases of individual half control rectifiers.

In half control circuits current of each phase can follow the references only through one half-cycle whereas the other half cycle current remains uncontrolled [2] and therefore can not follow the reference. In such a situation, the complementary side rectifier must compensate for the error due to its counterpart. Hence, an active filter type control configuration is added with the current references generated from the voltage controller. It can be seen from Fig. 2 that the individual rectifier reference currents are added to the error of the complimentary half to generate the final current references for the individual half controlled rectifiers. However, the current references through each phase of both the rectifiers are limited to half of the peak rated current. The current controller is chosen as regular hysteresis current controller. Depending on the direction of errors between the reference current and actual feed back currents through the phases, the switching of the devices is executed.

A low pass filter is added in the feedback path of the current in order to avoid the influence of switching frequency harmonics affecting the dynamics of the controller. Compared to [3] the proposed control algorithm appears to be much simpler. In the previous paper, two control loops consisting of PI controller were employed for controlling the bus voltages and the two outputs of the two PI controllers were processed in multiple stages in order to finally reach the current references for the individual rectifiers. However, in the present paper only one PI controller is needed. In addition, the number of stages involved to generate the final reference currents are also less.

By employing the proposed controller, it is expected that lower order harmonics both in AC and DC sides will be eliminated unlike the previously proposed controller [3] where appreciable even order harmonics were present in the DC bus voltages. It is mentioned earlier that the reference currents through each phase is limited to half the peak rated current of the combined rectifier. By utilizing this arrangement the currents through the active devices are restricted to half the rated current.

IV. SIMULATION RESULTS AND DISCUSSIONS

A 40kW 3-phase 415V, 60Hz system with 700V DC bus has been simulated in SABER along with an RL load. BJTs and power diodes available from SABER templates are used for simulating the proposed rectifier power circuit. An inductance of 500μH in the AC side is used as leakage inductance of the transformer for each phase of each half of the rectifiers. A 3300μF DC bus capacitor with an ESR of 0.015 ohms is considered in the above simulation. The resistance and inductance used for the load are 12.5 ohms and 100nH respectively.

The simulation results of the proposed rectifier with appropriate legends are presented in Figs 3-7. It may be seen from the simulation results that even though the currents through the secondary windings of the transformer (ia1 and ia2 in Figs 3 and 6) are highly distorted their combined waveforms which are reflected in the primary side of the transformer (ia, ib and ic)) are smooth and nearly sinusoidal. Also, the primary side currents are in phase with their respective source voltages (see Fig. 5 and Fig. 7). Thus, unity power interface of the system can be achieved.

The DC bus voltage is also very smooth and does not show any appreciable distortion (Figs 3, 5 and 7). Hence, it may be claimed that the proposed controller successfully eliminates the lower order harmonics both in AC and DC side of the proposed rectifier. The currents through the different semiconductor components at rated load are shown in Figs 3 and 4. It demonstrates that the currents through the switches (i(sw14) and i(sw24)) are limited to only 40A, which is half of the peak phase current 80A when the system operates at full load (40kW). Hence, it may be claimed that the proposed rectifier has reduced the rating of the active devices by almost 50% of the rated value without sacrificing the performance of the system. The same can be concluded for the upper half diodes of each half controlled rectifiers (i(d11) and i(d21)). In order to compare the legends in the plots the reader is referred to the schematic of the proposed rectifier in Fig. 1.

The lower half anti-parallel diodes (i(d14) and i(d24)) of each half controlled rectifier show almost the same peak current (80A) as that of the phase currents (ia, ib, ic). It may appear that these anti-parallel diodes are of full rated power. However, the final design value depends on the thermal limit of the junction temperature across each semiconductor components, which in turn depends on the losses incurred by the individual components. It may be observed (see Fig 4.) that these anti-parallel diodes conduct for an entire half cycle and the currents through them are zero for the other half cycle. Thus these diodes do not experience any switching current. Hence, it may be argued that the switching (turn-off) losses of these diodes are almost zero. Whereas the conduction losses may have been doubled at some operating point compared to their anti-parallel active switches (sw14, sw24). Thus conduction loss being higher and switching loss being zero, the total loss remains roughly the same across these diodes.

Normally a diode made for high switching frequency will be able to carry more rms current than its rated value when there is no switching loss across the same device. With this argument it may be concluded that for higher switching frequency (around 10kHz) should a switch

carry say 50A current, then its equivalent anti-parallel diode have no switching losses and may be able to carry approximately 100A current (assuming turn-off loss and conduction loss is comparable). The junction across can be maintained to its design value. Thus, if the thermal limit of the junction across the components are the criteria of designing the semiconductor devices then it may be argued that a half power rating diode still may be used for the proposed configuration, since the extra conduction loss is being compensated by virtually no switching loss. With this latest argument it may be concluded that all the 6 switches and 12 power diodes may be designed for half power rating for the proposed rectifier configuration.

In order to show that the system works well for all load conditions the typical simulation results at full load and 25% load at both steady-state and dynamic conditions are given in Figs 3-7. It may be seen that the source side currents (ia, ib, ic) are always smooth and sinusoidal and maintains the unity power factor operation independent of load. The DC bus voltage also shows satisfactory performance in all operating conditions.

In order to show the superiority of the proposed rectifier in comparison to multiple DC bus topology[3] the results of individual phase currents (ia1, ia2), their combined current waveform (ia) and the DC bus voltage along with their FFTs are given in Fig. 8a and Fig. 8b respectively for a full load condition. It may be seen that with the proposed method the combined current waveform as well as the DC bus voltage is almost free from lower order harmonics even though the individual phase currents (ia1, ia2) have considerable lower order even harmonics.

To demonstrate the performance of the rectifier when the active filtering algorithm is not included in the control scheme, the simulation results are shown in Fig. 9a and 9b respectively. It may be seen that with such operation both the combined phase current (ia) and DC bus voltage (vdc) contains lower order harmonics, however the harmonic content is less on the DC side compared to AC side and also both sides contain odd harmonics rather than usual even harmonics. This result is because the even harmonics for upper and lower phase are cancelled.

V. CONCLUSION

The potential of the complementary half-bridge converters connected to a common DC link has been investigated in this paper. It is illustrated that with the proposed configuration similar performance of a regular 3-phase full controlled rectifier can be achieved and in addition the ratings of the active switches can be reduced to half the rated power.

A much simpler control algorithm compared to [3] is proposed here. The typical problems of a half controlled circuits like low order even harmonics both in AC and DC side are eliminated. The acoustic noise and losses across the individual set of inductors are reduced by complementary configuration of the transformer and including the line inductances as a part of the transformer leakage.

By choosing both the half control circuits as common emitter type the isolated power supply requirement for the gate drivers are eliminated. In addition, the proposed topology is shoot through safe.

The efficiency with the proposed rectifier is also expected to be higher since the switching losses across the device will be reduced due to lower switching currents though the switches and diodes. A detailed efficiency comparison of the proposed rectifier and a regular rectifier will be taken up as a future work.

The flip side of the proposed rectifier compared to a regular 3-phase fully controlled rectifier is that two more extra current sensors are needed for measuring the currents of two independent half controlled rectifiers. Also, the regenerative operation of a regular full bridge rectifier is sacrificed in the proposed configuration. However, in most applications regenerative operation is not required. For example, in drive applications the dynamics of the machine being much faster than the dynamics of the front end converter, it is not always possible to feed the regenerative energy from the machine into the source in real time. The preferred approach for such case is to place a braking resistor across the DC bus and dissipate the regenerative energy across the resistor.

Hence, for applications where regenerative operation of the rectifier is redundant, the proposed topology could provide distinct advantages compared to the existing solution with respect to system cost, device rating, ruggedness and system efficiency.

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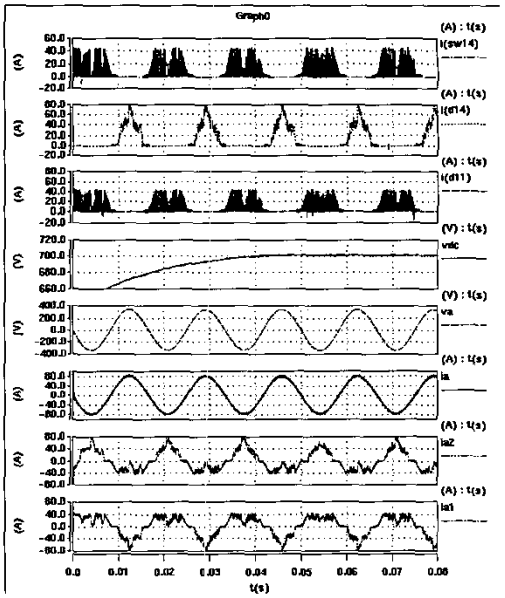

Fig. 3 Simulation results at full load (40kW) (Refer to Fig. 1 for legends of the plot)

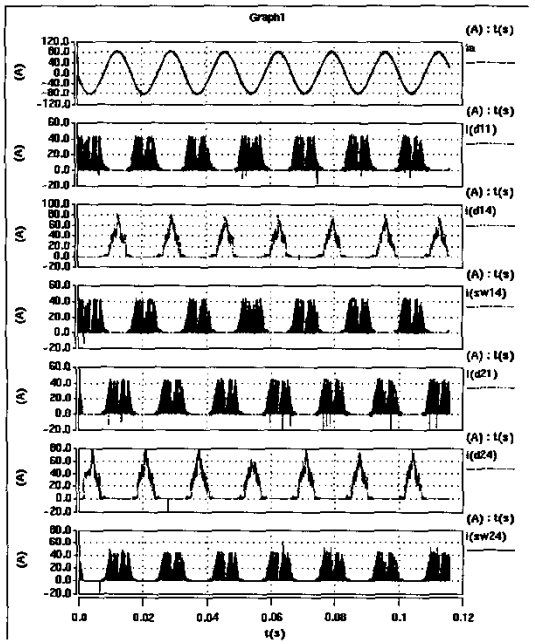

Fig. 4 Current through different components at full load (Refer to Fig. 1 for legends of the plot)

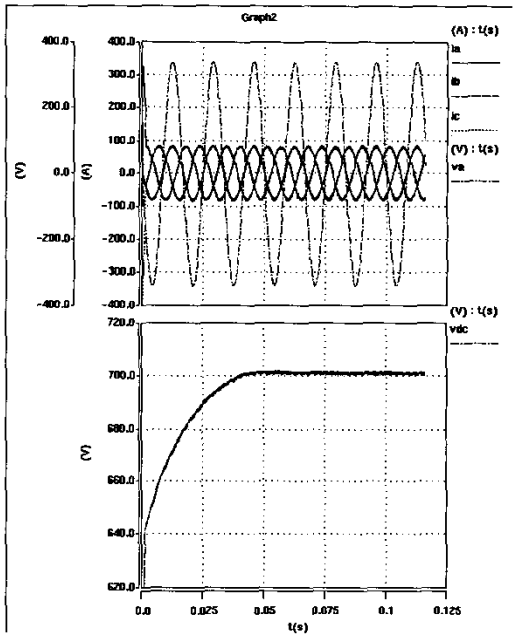

Fig. 5 Phase voltage, currents and DC bus volatges at full load (Refer to Fig. 1 for legends of the plot)

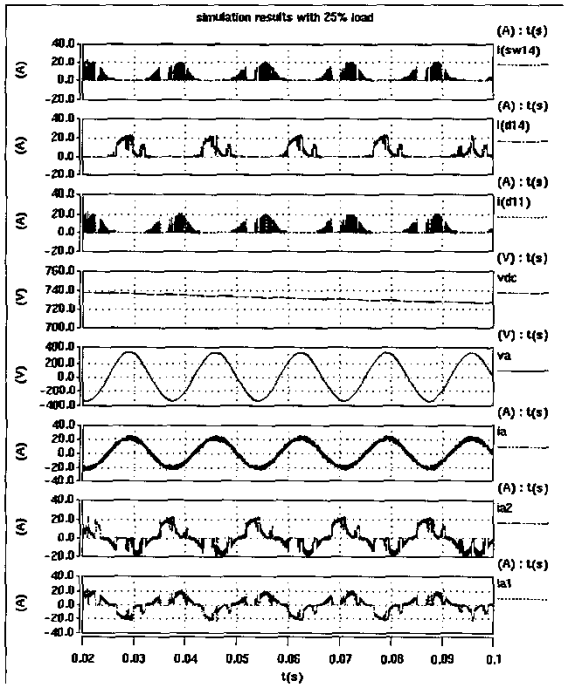

Fig. 6 Simulation results at 25% load (Refer to Fig. 1 for legends of the plot)

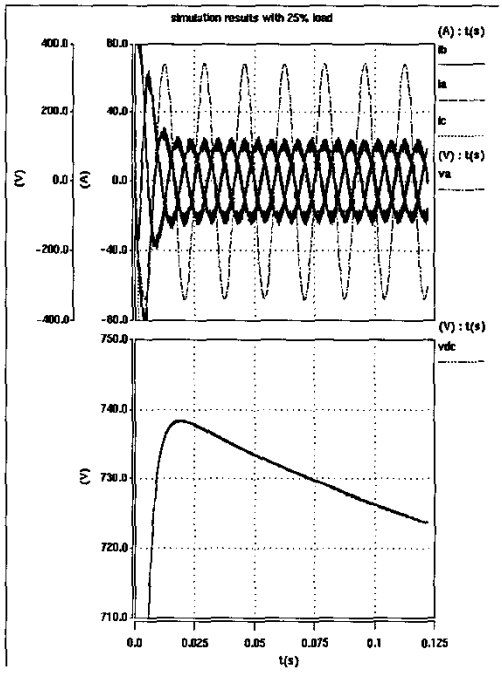

Fig. 7 Simulation results at 25% load (Refer to Fig. 1 for legends of the plot)

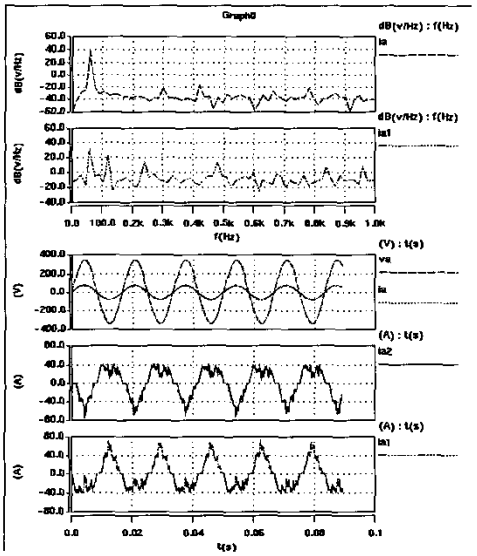

Fig. 8a Simulation results of phase currents for individual half controlled rectifiers (ia1, ia2) along with their combined current waveform (ia) and corresponding FFT when operating at full load with proposed active filtering algorithm. (Refer to Fig. 1 for legends of the plot)

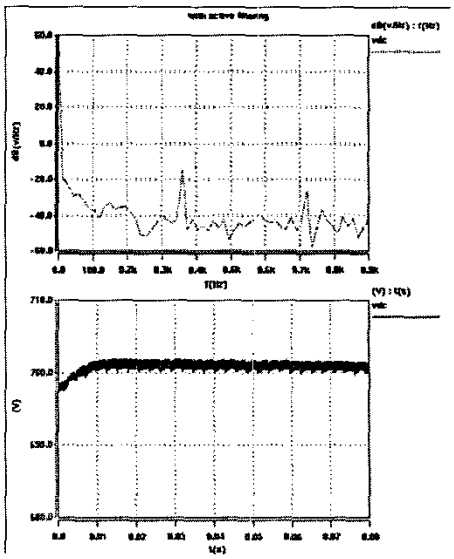

Fig. 8b Simulation results of combined DC bus voltage (vdc) and corresponding FFT when operating at full load with the proposed active filtering algorithm (Refer to Fig. 1 for legends of the plot)

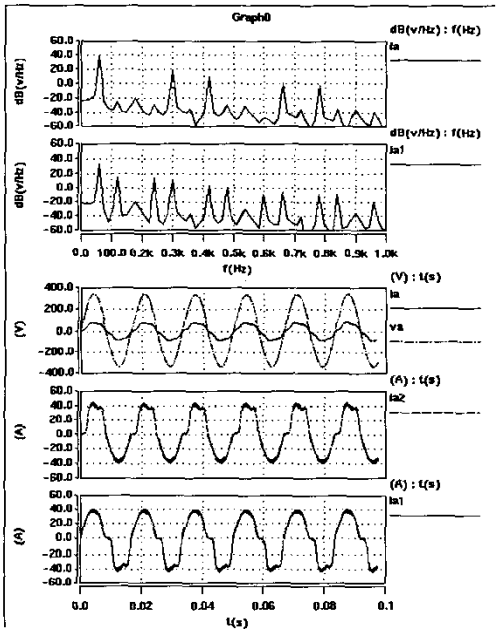

Fig. 9a Simulation results of phase currents for individual half controlled rectifiers (ia1, ia2) along with their combined current waveform (ia) and corresponding FFT when operating at full load and without active filtering scheme. (Refer to Fig. 1 for legends of the plot)

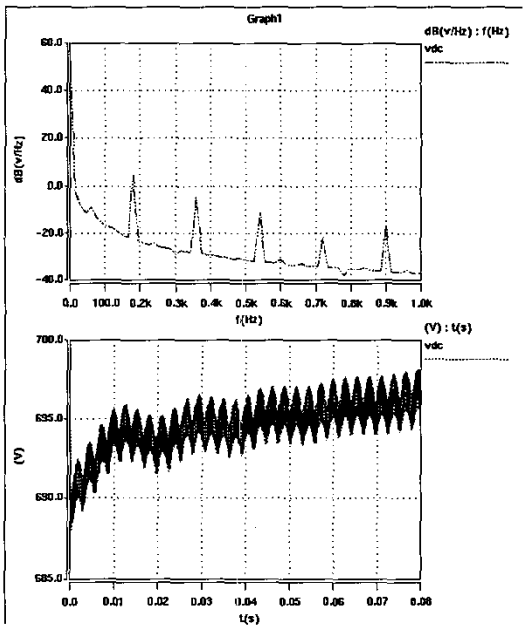

Fig. 9b Simulation results of combined DC bus voltage (vdc) and corresponding FFT when operating at full load and without active filtering scheme. (Refer to Fig. 1 for legends of the plot)

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