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Design and Implementation of Current–Fed Boost Converter Using Fuel Cell Concept

KEYWORDS Fuel Cell, Active clamp, leakage inductance, three-phase dc/dc converter, three-phase pulse width modulation (PWM) strategy, voltage transfer ratio, zero-voltage switching (ZVS).

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ABSTRACT – *This paper concentrates on a three-phase dc/dc converter with high efficiency and voltage boosting capability designed for use in the interface between minimum voltage fuel cell concept and it is also used for high voltage dc bus for inverters. Zero-voltage switching in all active switches is achieved through using a common active clamp branch and zero current switching in the rectifier diodes is achieved through discontinuous current conduction in the secondary side. The converter is capable of increased power transfer due to its three-phase power configuration. It reduces the RMS current per phase and reduces conduction losses. A delta-delta connection on the three-phase transformer provides parallel current paths and reduces conduction losses in the transformer windings. An efficiency of above 93% is achieved through both improvements in the switching and through reducing conduction losses. A high voltage ratio is achieved by combining inherent voltage boost characteristics of the current-fed converter and the transformer turns ratio. The proposed converter, a three-phase PWM strategy and fuel cell concept is simulated.*

I. INTRODUCTION

Fuel cells are identified as a future source of generating energy due to their efficient and clean energy characteristics. The Fuel cells are producing low-varying dc voltage in the range of 30–60 V for static power application such as residential use. For static fuel cells, the power conditioning system usually consists of a low-voltage fuel cell as the primary source, a dc/dc converter to obtain isolated high voltage and a dc/ac inverter to connect commercial ac voltage [1]. Since a dc/ac inverter supplies power into a 220V ac utility, an isolated dc/dc converter has to convert low varying dc voltage to high constant dc voltage at around 370 V [2]. Therefore dc/dc converter with a high voltage ratio is needed, and a transformer is usually employed for boosting voltage as well as isolation. However high leakage inductance in the transformer leads to trouble such as voltage spikes and electromagnetic noise.

In order to achieve a high voltage ratio while limiting the overshoot in the turn-off voltage caused by the leakage inductance, a current-fed dc/dc converter with an active clamp has been introduced in the push–pull topology and full-bridge topology for all single–phase application [3]. In addition, a soft-switching active clamp scheme has been proposed to minimize turn-off losses in the clamp switch. These converters have been shown to perform quite well, but the single-phase circuits face severe components stress and degraded efficiency for higher power levels.

In high-power applications research has been focused on the three-phase dc/dc converter due to the benefits it can offer, such as high power density and high-quality waveforms. Biogas introduced three-phase converter topology in the high-frequency dc/dc conversion area, and showed that three-phase structure had superior potentials in power density, RMS current through switches, size of reactive components, and efficiency compared to a relevant single-phase structure [4]. However negligible leakage inductance is required in the three-phase transformer implementation and switches commutate in the hard switching condition.

A series resonant converter comprised of resonant capacitors, stray inductances of the transformer and equivalent resistances was proposed for the three-phase converter and showed variable switching frequency with limited parameter tolerance. However the series resonant converter results in an increase at the volume of reactive components. Zero-voltage switching (ZVS) commutation using leakage inductances in the transformer and intrinsic capacitances in the switches was introduced in three-phase dc/dc converter and achieved high power density with simple power structure [5]. Since ZVS commutations are occurred in the same way as a single-phase phase shift- modulated full-bridge converter, so ZVS actions are limited in higher load condition.

A six-leg three-phase converter was introduced along with phase-shift modulation and increased voltage transfer ratio by Y connection of secondary side of three single-phase transformers [6]. Although the six-leg converter showed very high efficiency without auxiliary snubber circuits, the six-leg converter requires more switches and control circuit complexity.

II. THREE –PHASE DC/DC CONVERTER

Fig.1 shows the proposed three-phase dc/dc converter with an active clamp. It consists of a three-phase current-fed converter, whose outputs are connected to a three-phase full-bridge diode rectifier through a delta-delta wound three-phase transformer. The three-phase current-fed converter is divided into a three-phase full-bridge converter configured as six main MOSFET switches (S1–S6) for three-phase dc/ac conversion, one auxiliary MOSFET switch (Sc) and clamp capacitor Cc for the active clamp and a dc boost inductor L_{dc} acting as a current source.

It reduces switching losses and leads to a highly efficient, isolated voltage boost converter. It should be noticed that the three-phase transformer can be given the form of three discrete single-phase transformers connected in delta-delta winding or a three-legged transformer commonly used in the utility line.

Due to these advantages this converter is highly recommended as the interface between a low-voltage high-power fuel cell source and a succeeding inverter stage. It is also suitable for other low-voltage sources such as batteries and photovoltaic array, which supply high-voltage, high-power dc to the next power stages.

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III. PWM STRATEGY

Fig.2 shows a simplified circuit of the proposed three-phase dc/dc converter introduced. The delta-delta wound three-phase transformer is represented by its three leakage inductances L_{lk} and its output voltage V_o on the secondary side is referred to on the primary side as Vo. It is assumed clamp capacitor Cc and output capacitor Co are infinite in value; these are referred to by voltage sources V_c and V_o respectively. The boost inductor L_{dc} can be replaced by a current source Id during each switching period.

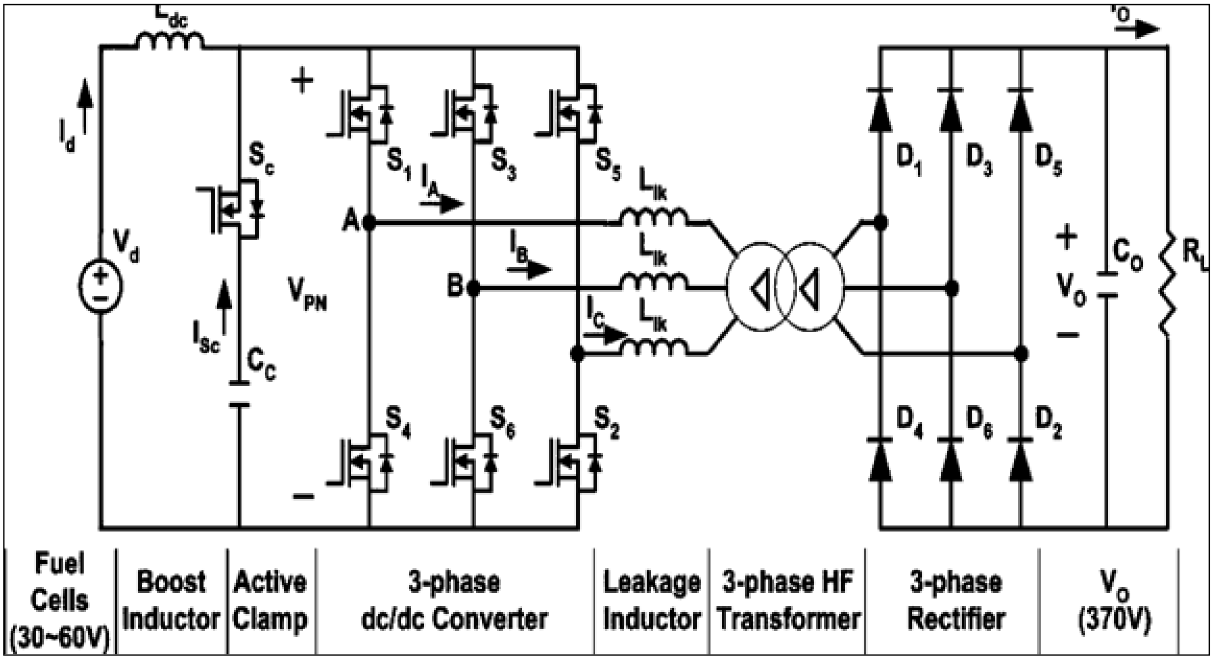


Fig.1. Power Circuit Configuration of Three-Phase Current-fed DC/DC Converter with Active Clamp

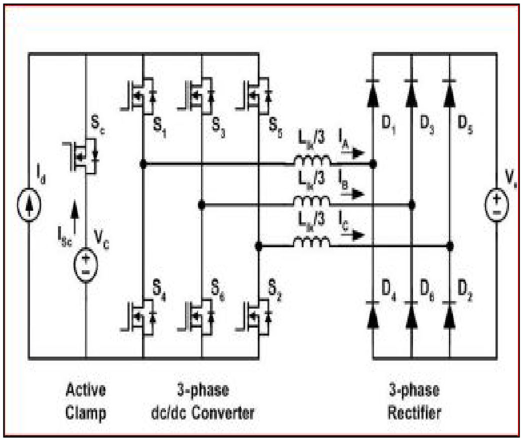


Fig.2. Circuit simplified through replacement of the three-phase transformer with leakage inductance L_{lk}

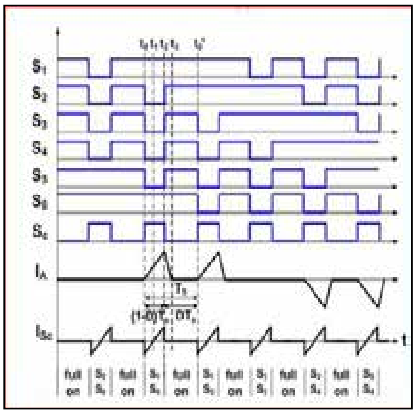
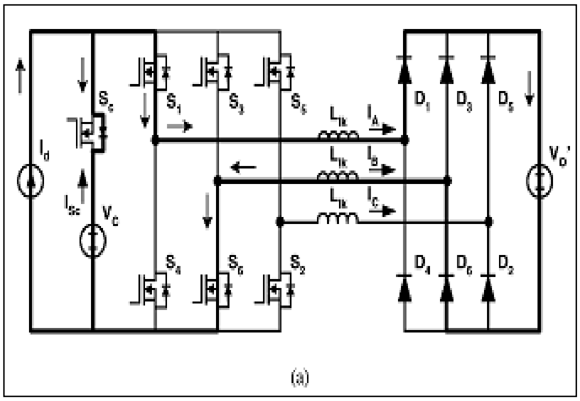
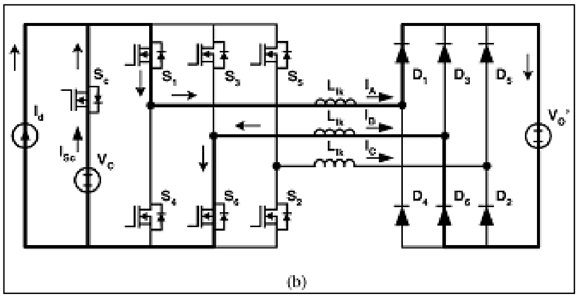


Fig.3. waveforms of the proposed converters

Fig.3 shows the ideal current waveforms of phase A current I_a and clamp current I_{sc}, the gating signals for main switches S1–S6, and clamp switch SC together with corresponding working switch pairs. Duty ratio D is defined as an interval when all main switches are turned on and boost inductor L_{dc} charges energy from input V_d.





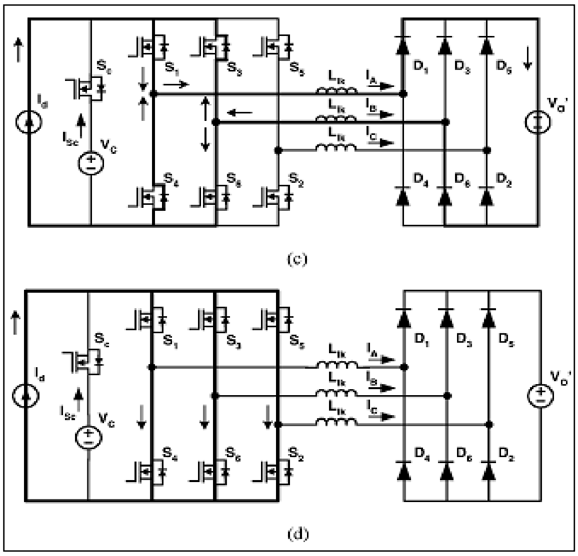


Fig.4. Topological states of active clamp three-phase boost converter

(a) t_0–t_1 (b) t_1-t_2 (c) t_2 –t_3 (d) t < t_0 , t_3 –t'_0

IV. PWM CONTROL FOR BUCK MODE OPERATION

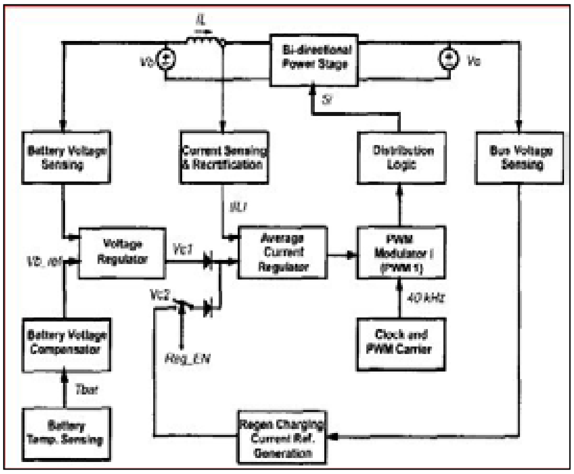


Fig.5. Block Diagram of PWM Control in Buck mode

The block diagram of PWM control generation in buck mode is shown in Fig.5. In this mode also referred to as charging mode, the battery gets charged and is regulated at the voltage given by the battery voltage reference signal which is compensated with battery temperature.

V. PWM CONTROL FOR BOOST MODE OPERATION

It is obvious from the timing analysis in that the proposed non-phase-shifting PWM for boost mode operation mandates two phases of PWM signals, which are phase, shifted by 180° and have a duty-cycle range from almost 100 percent. Unfortunately, no single PWM controller can fulfill these requirements of functionality.

One solution to the problem is presented in the block diagram for PWM control generation in boost mode in Fig.6. In this scheme, a pair of PWM controllers PWM 2 and PWM 3 are synchronized with a pair of master clocks, which are out of phase, to ensure the 180^0 phase difference.

In reality, such a pair of clocks are readily available from PWM I for the buck mode operation.

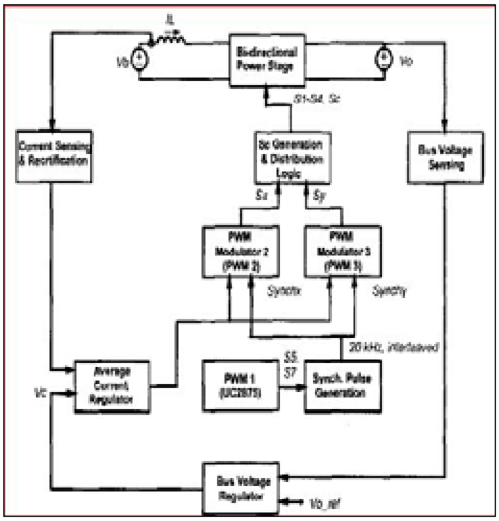


Fig.6. Block Diagram of PWM Control in Boost mode

Block Diagram of PWM Generator

Fig.7. shows a block diagram of the PWM generator that forms PWM patterns for six bridge switches and one clamp switch. DSP 320LF2407 calculates six signals and one full activation signal for the seven switches mentioned before the signals are transferred to FPGA, where dead time is inserted for zero-voltage switching operation and final PWM patterns are generated. Fig.8. shows PWM patterns generated by FPGA and exhibits gate signals for S_1, S_2, S_3, S_4, S_5, S_6 and SC from top to bottom, respectively.

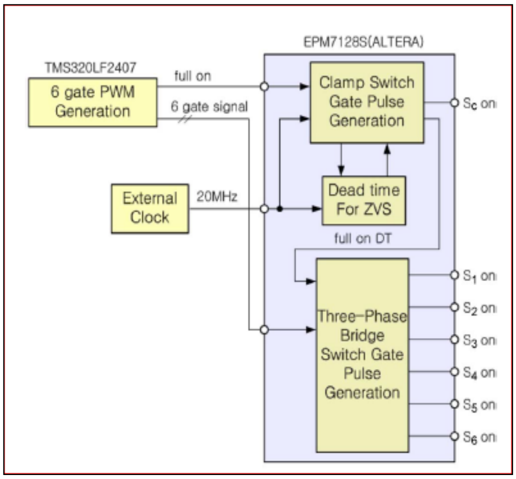


Fig.7. Block Diagram of PWM Genarator

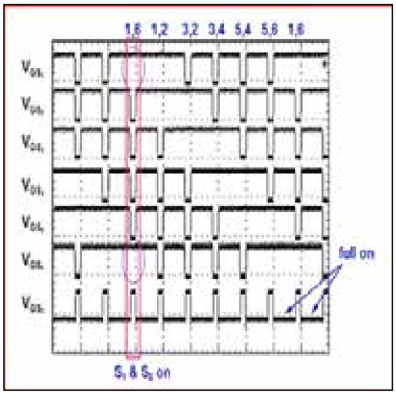


Fig.8. PWM patterns from FPGA

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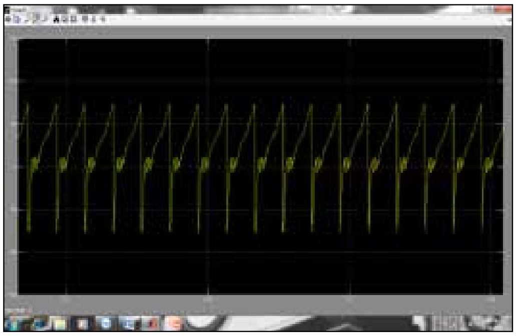
The following waveforms are under 30 V for input voltage, at 370 V for output voltage and at a 500-W load with the same parameters used in the simulation. Fig. shows a primary phase current I_A of phase A at duty D = 0.75 and matches the simulation waveform in Fig. shows dc inductor currents I_d and I_A, where I_A delivers power to the load during the discharging interval of dc inductor L_{dc}. DC inductor current I_d increases during full turn-on interval DTS, when dc inductor

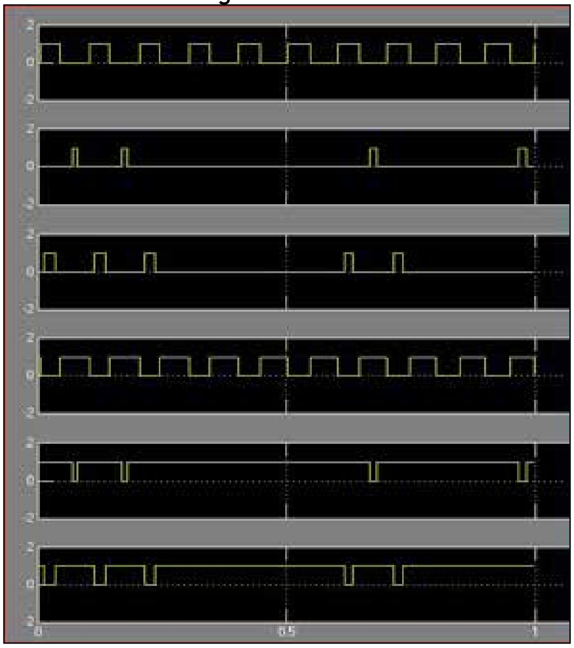
Charges energy from input source V_d and decreases during (1−D) TS when dc inductor discharges energy to output capacitor through L_{lk}. The difference of Id and IA are buffered by clamp capacitor C_S and current conflicts between L_{dc} and Llk are resolved.

VI. SIMULATION RESULTS

Simulation Results of Input Current



Simulation Results of generation of Gate Pulses



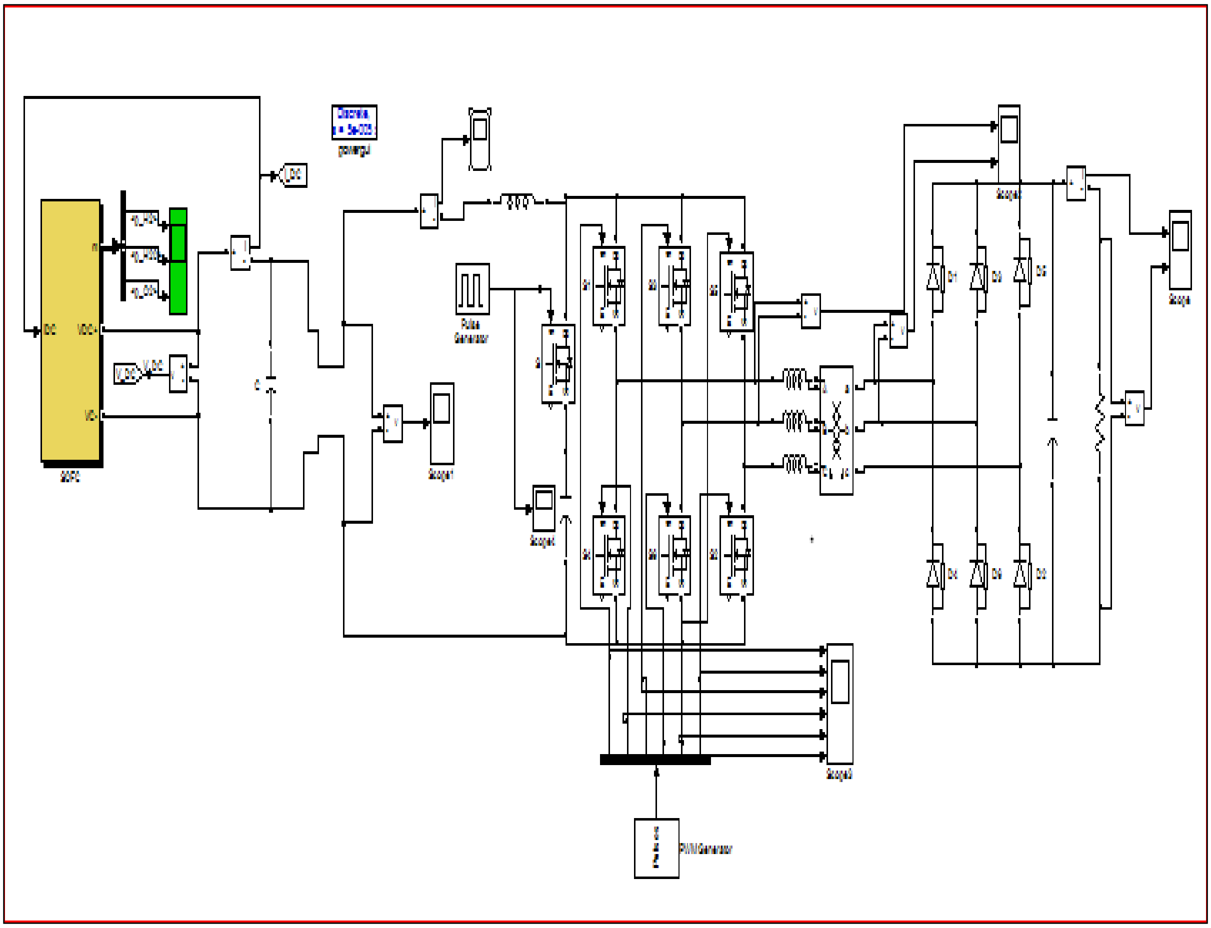
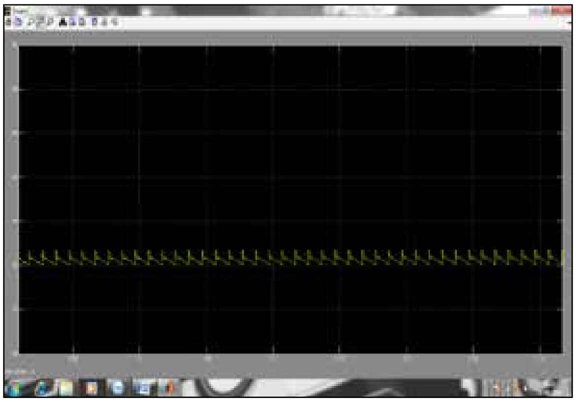
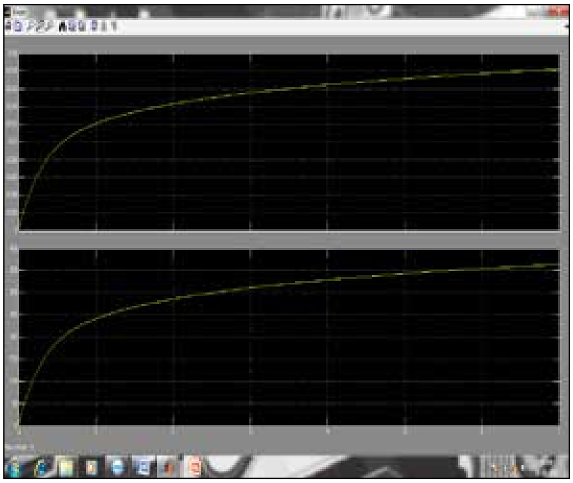


Fig.9. Simulation Model of Current –Fed Boost Converter Using Fuel Cell Concept

Simulation Results of Input Voltage



Simulation Results of Output Voltage and Output Current



VII. CONCLUSION

This paper concludes fuel cell concept, a current-fed boost converter with an active clamp and PWM strategy have designed. The converter would have ZVS in all active switches. This would be achieved through using the common active clamp branch, zero current switching in the rectifier diodes and thus producing discontinuous current conduction. The converter has been shown to be capable of increased power transfer due to its three-phase power configuration and it reduces the RMS current per phase. A delta-delta connection on the three-phase transformer provides parallel current paths and reduces conduction loss in the transformer windings. Reductions in both the switching and conduction losses results in converter efficiency of above 93%. Inherent voltage boost characteristics of the current-fed converter increase the voltage transfer ratio in addition to the transformer turns ratio. It shows that the converter can be realized with smaller sized filter components, which leads to higher power density. These advantages make this converter suitable for low dc voltage renewable energy sources such as fuel cells and photovoltaic cells.

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