

A Novel Isolated DC-DC Converter for High Step-Up Ratio for Railway Applications

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Abstract: This paper focuses on the design of an isolated dc–dc converter for railway applications and the requirements for the investigated DC-DC converter. First of all the voltage should be stepped up to sufficient level at which the DC/AC conversion can be performed to AC mains voltage requirements. Overall performance of the renewable energy system is then affected by the efficiency of step-up DC/DC converters, which are the key parts in the system power chain. This review is focused on high efficiency step-up DC/DC converters with high voltage gain. Although DC/DC-converters exist without input-output isolation, most DC/DC-converters use an internal transformer and the output is electrically (galvanically) isolated from the input. The basic input to output isolation can be used to provide either a simple isolated output power source, A high step-up converter adopts boost converter with interleaved mode and a coupled inductor to increase its step-up voltage ratio. The interleaving technique connects the converter in parallel to share the power flow, this reduce the size, weight, and volume of the inductors and capacitors. Without using of high duty ratio this converter achieves a high step-up voltage-conversion ratio through a coupled inductor and the converter. The proposed concept can be implemented to isolated DC-DC converter high step up ratio gain for grid connected applications by using MATLAB/SIMULINK software.

Keywords: DC–DC Power Conversion, Power Electronics, Power Supplies, Rail Transportation Electronics.

I. INTRODUCTION

Solar energy is the most low cost, competition free, universal source of energy as sun shines throughout. This energy can be converted into useful electrical energy using photovoltaic technology. The steady state reduction of price per peak watt and simplicity with which the installed power can be increased by adding panels are attractive features of PV technology. Among the many applications of PV energy, pumping is the most promising. In a PV pump storage system, solar energy is stored, when sunlight is available as potential energy in water reservoir and consumed according to demand. There are advantages in avoiding the use of large banks of lead acid batteries, which are heavy and expensive and have one fifth of

the lifetime of a PV panel. A number of simulation DC motor driven PV pumps are already in use in several parts of the world, but they suffer from maintenance problems due to the presence of the commutator and brushes. Hence a pumping system based on an induction motor can be an attractive proposal where reliability and maintenance-free operations with less cost are important. The effective operation of Induction motor is based on the choice of suitable converter-inverter system that is fed to Induction Motor. For PV applications like pumping these converters could do a good job as pumping is carried out at high power. Thus a new push pull converter which is two switch topology can do justice by giving a high power throughout. The Induction Motors are the AC motors and hence from converter, an inverter system is also required to obtain an AC voltage. This inverter is chosen based on its advantages and it is fed to induction motor.

Photovoltaic technology is one of the most promising for distributed low-power electrical generation. The steady reduction of price per peak watt over recent years and the simplicity with which the installed power can be increased by adding panels are some of its attractive features. Among the many applications of photovoltaic energy, pumping is one of the most promising. In a photovoltaic pump-storage system, solar energy is stored, when sunlight is available, as potential energy in a water reservoir and then consumed according to demand. There are advantages in avoiding the use of large banks of lead-acid batteries, which are heavy and expensive and have one-fifth of the lifetime of a photovoltaic panel. It is important, however, that the absence of batteries does not compromise the efficiency of the end-to-end power conversion chain, from panels to mechanical pump. Photovoltaic panels require specific control techniques to ensure operation at their maximum power point (MPP). Impedance matching issues mean that photovoltaic arrays may operate more or less efficiently, depending on their series/parallel configuration.

II. TOPOLOGY OVERVIEW

The field of high-power-density dc–dc converters has been addressed often in the last decades. From the beginning, the

conventional full-bridge converter topology has been the preferred choice to realize a high-power dc–dc converter [1]. However, due to problems with the leakage inductance of the transformer and, consequently, reverse recovery losses of the output diodes, the maximum switching frequency is limited. To solve this problem, several solutions were presented, including active clamps and/or auxiliary circuits [2]–[4]. These solutions enable higher switching frequencies at the expense of additional components and could lead to higher device stress. The additional components impede the increase in power density and increased complexity, while the efficiency is often not better compared to other zero-voltage switching (ZVS) and zero-current switching (ZCS) techniques. Resonant converter topologies offer possibilities for ZVS or ZCS, enabling high efficiencies and power densities [5]–[7]. The series resonant or LLC converter provides a load independent operating point with unity voltage gain at a switching frequency near the resonance frequency [6], [8]–[10]. However, this load independent operating point is lost when the input and/or output voltage changes, and switching frequency control is necessary to regulate the output voltage. Therefore, a boost converter can be used to regulate the input voltage in order to guarantee operation in the load independent operating point [10], [11].

Alternatively, the resonance circuit can be influenced by a switch-controlled capacitor, resulting in fixed frequency operation [12]. Despite the provided solutions, the LLC converter still suffers from high rms phase currents, requiring a relatively large series resonant capacitor that leads to a decreased power density. The additional boost converter or switch-controlled capacitor also deteriorates the power density and efficiency. The dual active bridge (DAB) topology introduced in [1] is an attractive alternative to the problems with the classical full-bridge topology. In comparison with the conventional full bridge topology, the output inductor is transferred to the ac side, and is in series with the leakage inductance. Consequently, the energy in the leakage inductance is transferred to the load without causing reverse recovery losses in the output diodes. This allows higher switching frequencies and, therefore, an increase in power density. Furthermore, the use of an active output bridge also increases the power density of the transformer [1]. When the desired inductance can be incorporated in the transformer, again the power density can be increased. In [13], very high power densities, up to 11.13kW/L, are reported. A three-phase DAB, also proposed in [1], has some advantages in comparison to the single-phase DAB. The three-phase DAB has lower turn-off currents in the switches and lower rms currents per phase. Also, the VA ratings for the input and output filters are significantly lower and can even go to zero due to the three-phase characteristics.

Besides the lower VA ratings, the effective ripple frequency of the filter currents is three times higher, allowing to use smaller filters. Compared to the single-phase DAB, the currents through the transformer windings are much more sinusoidal, resulting in reduced high frequency losses in the

transformers [14]. A comprehensive comparison of single-phase and three-phase DAB topologies is given in [1]. Both the single-phase and three-phase DAB topologies suffer from a limited soft-switching range in case the input voltage and the reflected output voltage are not equal. For the single-phase DAB, there exist switching strategies or modulation schemes for increasing the soft-switching range. These are described. Here, the soft-switching operating range is increased and also the overall efficiency can be increased with a minimum loss modulation strategy. The three-phase DAB does not possess these advantageous switching possibilities. The phase shift angle ϕ between the bridge voltage is the only control variable as the symmetrical properties of the three-phase system have to be maintained [14]. Although the three-phase DAB has less switching possibilities, compared to the single-phase DAB, and includes four extra switches, the topology has the most preferred properties for designing a high-power density isolated dc–dc converter. It has the lowest component ratings and is capable of achieving higher output powers with possibly the highest power density. For APU applications in light rail vehicles, high-power capability and power density are decisive. Therefore, the three phase DAB topology is selected in this study.

III. THREE-PHASE DAB DC–DC CONVERTER

The three-phase DAB, shown in Fig. 1(a), consists of two three-phase bridges coupled with a three-phase transformer connected in Y–Y. The bridges are operated in six-step mode at a constant frequency. By applying a phase shift between the input and Output Bridge, the power flow can be controlled. Because the converter is symmetrical from input to output, bidirectional power flow is possible. The transformer leakage inductances are used as current transfer elements and, therefore, not considered as parasitic. If the magnetizing inductance L_m is neglected, an equivalent circuit can be used for analysis. In this circuit, only the total leakage inductance L_s seen from the primary side is connected between the phase legs from the input and output bridge. The corresponding idealized waveforms are shown in Fig. 1(b).

A. Analysis

To analyze the soft-switching region, the current of phase A is defined for the first six intervals as depicted in Fig. 1(b). The current i_A in the different intervals is given in (3) for phase shifts of $0 \leq \phi \leq \pi/3$. For phase shifts of $\pi/3 \leq \phi \leq 2\pi/3$, a second set of equations, not given here, is utilized for further analysis of the soft-switching region. The magnetizing inductance L_m of the transformer is neglected in the analysis. Furthermore, the angular frequency is defined as $\omega = 2\pi f_s$, with f_s the switching frequency in Hertz. The transformer's leakage inductance is indicated with L_s and the input and output voltage are defined as V_i and V_o , respectively. The reflected output voltage is given by $V_o = V_o/N$, with N the turns ratio of the transformer. Because the phase current is symmetric, the current $i_A(0)$ can be found by solving the set of equations, assuming steady-state

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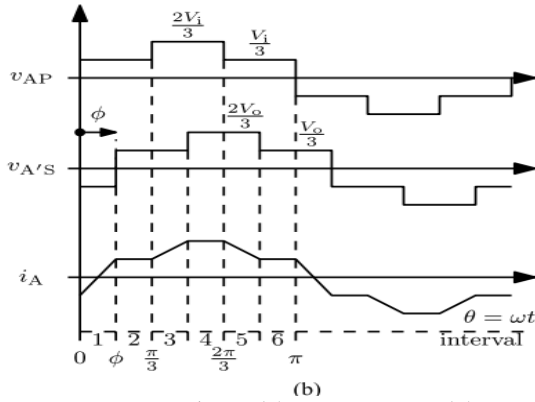
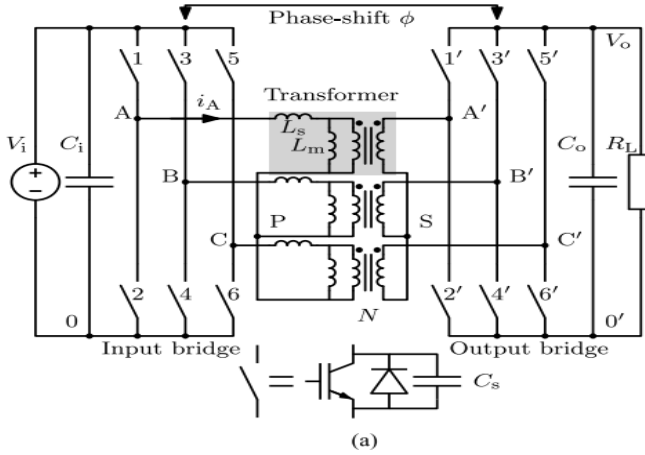


Fig.1. Three-phase DAB. (a) Topology. (b) Idealized waveforms, gating signals can be found in [1].

Condition $i_A(0) = -i_A(\pi)$. This results in

$$i_A(0) = \frac{1}{3\omega L_s} \left[\frac{2\pi}{3} (V_o' - V_i) - V_o' \phi \right] \quad (1)$$

B. Output Power

Under the assumption of a lossless converter, the output power P_o can be found with

$$P_o = P_i = \frac{3}{\pi} \int_0^\pi v_{AP}(\theta) i_A(\theta) d\theta \quad (2)$$

$$i_A(\theta) = \begin{cases} i_A(0) + \frac{V_i + V_o'}{3\omega L_s} \theta & \forall 0 \leq \theta \leq \phi & \text{:interval 1} \\ i_A(\phi) + \frac{V_i - V_o'}{3\omega L_s} (\theta - \phi) & \forall \phi \leq \theta \leq \frac{\pi}{3} & \text{:interval 2} \\ i_A(\frac{\pi}{3}) + \frac{2V_i - V_o'}{3\omega L_s} (\theta - \frac{\pi}{3}) & \forall \frac{\pi}{3} \leq \theta \leq \frac{\pi}{3} + \phi & \text{:interval 3} \\ i_A(\frac{\pi}{3} + \phi) + \frac{2V_i - 2V_o'}{3\omega L_s} (\theta - \frac{\pi}{3} - \phi) & \forall \frac{\pi}{3} + \phi \leq \theta \leq \frac{2\pi}{3} & \text{:interval 4} \\ i_A(\frac{2\pi}{3}) + \frac{V_i - 2V_o'}{3\omega L_s} (\theta - \frac{2\pi}{3}) & \forall \frac{2\pi}{3} \leq \theta \leq \frac{2\pi}{3} + \phi & \text{:interval 5} \\ i_A(\frac{2\pi}{3} + \phi) + \frac{V_i - V_o'}{3\omega L_s} (\theta - \frac{2\pi}{3} - \phi) & \forall \frac{2\pi}{3} + \phi \leq \theta \leq \pi & \text{:interval 6} \end{cases} \quad (3)$$

Finally, the expression of the output power for $0 \leq \phi \leq 2\pi/3$ is

$$P_o = \begin{cases} \frac{V_i V_o'}{\omega L_s} \phi \left[\frac{2}{3} - \frac{\phi}{2\pi} \right] & \text{for } 0 \leq \phi \leq \frac{\pi}{3} \\ \frac{V_i V_o'}{\omega L_s} \left[\phi - \frac{\phi^2}{\pi} - \frac{\pi}{18} \right] & \text{for } \frac{\pi}{3} \leq \phi \leq \frac{2\pi}{3} \end{cases} \quad (4)$$

C. Soft-Switching Region

Minimizing the switching losses is the key to achieve a high switching frequency. The turn-on losses are of main

interest because excessive losses in the switch and the anti parallel diode can arise when the anti parallel diodes experience the reverse recovery process. The input bridge faces this problem when $i_A(0) > 0$. Therefore, the current has to fulfill $i_A(0) \leq 0$ to ensure soft-switching in the input bridge. During the switching transient, the current i_A is considered constant. Rewriting (1) to the required constraint gives the phase shift for ensuring soft turn-on of the switches in the input bridge, this is found to be

$$\phi_i \geq \frac{2\pi(V_o' - V_i)}{3V_o'} \quad (5)$$

A similar derivation can be made for the output bridge, where the output bridge is soft-switching for $i_A(\phi) \geq 0$. Using (3) and (1) gives the required phase shift to ensure soft turn-on of the switches in the output bridge, resulting in

$$\phi_o \geq \frac{2\pi(V_i - V_o')}{3V_i} \quad (6)$$

Impact of ZVS Capacitors: ZVS capacitors, or snubber capacitors, are used to reduce turn-off losses. These are connected in parallel to the switches and supplement the output capacitance, as can be seen in Fig. 1(a). After a switch turns OFF, there is a small blanking time t_b before the opposite switch of the same leg turns on. During t_b , the current commutates to the ZVS capacitors and divides equally over the two capacitors of the phase leg. In this transition, one capacitor is charged while the other is discharged. This implies that the load current must be high enough to enable a full charge or discharge of the ZVS capacitors for a given t_b . Assuming a constant current during the switching transient, the soft-switching constraint for enabling soft turn-on of the switches in the input bridge is changed to

$$i_A(0) + \frac{2C_s V_i}{t_b} \leq 0 \quad (7)$$

and for the output bridge to

$$i_A(\phi) - \frac{2C_s V_o'}{t_b N} \geq 0 \quad (8)$$

Where C_s represents a ZVS capacitor connected in parallel to the switch, and t_b is a fixed blanking time. A more accurate, current depending charge-based ZVS analysis is reported. However, to investigate the impact of the ZVS capacitors and approximate the soft-switching region, the presented current based method is sufficient. Solving (7) and (8) for the phase-shift ϕ gives the soft switching region for the input bridge and the output bridge, respectively. These are given by

$$\phi_i \geq \frac{2\pi_i(V_o' - V_i)}{3V_o'} + \frac{2C_s V_i}{V_o' t_b} 3\omega L_s \quad (9)$$

$$\phi_o \geq \frac{2\pi(V_i - V_o')}{3V_i} + \frac{2C_s V_o'}{V_i t_b N} 3\omega L_s \quad (10)$$

D. Extension of the Soft-Switching Region

Auxiliary power converters for railway applications have to be able to operate from no-load to full-load conditions over the whole input voltage range. This means that the converter has to operate outside the soft-switching region. Therefore, two methods to extend the soft-switching operation of the converter have been investigated.

Auxiliary Inductors: The first method is based on adding reactive currents to fully charge or discharge the ZVS capacitors during the switching transient. The reactive currents are injected with three star-connected auxiliary inductors per bridge. This has the same effect as the magnetizing inductances of the transformers, which are also connected in star. However, separate auxiliary inductors are preferred to have more design flexibility. The peak current, injected by the auxiliary inductors during the switching transient, is calculated from the voltage waveforms shown in Fig. 1(b). For the input bridge, the peak current is calculated as

$$\hat{i}_{a-i} = \frac{2\pi V_i}{9\omega L_{a-i}} \quad (11)$$

and for the output bridge as

$$\hat{i}_{a-o} = \frac{2\pi V_o}{9\omega L_{a-o} N} \quad (12)$$

Next, the soft-switching constraints from (7) and (8) can be extended to

$$i_A(0) + \frac{2C_s V_i}{t_b} - \frac{2\pi V_i}{9\omega L_{a-i}} \leq 0 \quad (13)$$

and for the output bridge to

$$i_A(\phi) - \frac{2C_s V_o}{t_b N} + \frac{2\pi V_o}{9\omega L_{a-o} N} \geq 0 \quad (14)$$

Then, the soft-switching region can be calculated with the minimum phase shift for the input bridge

$$\phi_i \geq \frac{2\pi(V'_o - V_i)}{3V'_o} + \frac{2C_s V_i}{V'_o t_b} 3\omega L_s - \frac{2\pi V_i L_s}{3V'_o L_{a-i}} \quad (15)$$

and for the output bridge

$$\phi_o \geq \frac{2\pi(V_i - V'_o)}{3V_i} + \frac{2C_s V_o}{V_i t_b N} 3\omega L_s - \frac{2\pi V_o L_s}{3V_i L_{a-o} N} \quad (16)$$

As shown with (15) and (16), the auxiliary inductance decreases the required phase-shift for operating in a soft-switching manner. To achieve soft-switching in the whole operating range, (15) and (16) should be solved for zero phase-shift, i.e., no-load condition. The corresponding values for L_{a-i} and L_{a-o} are low and, therefore, also causing high reactive currents. The use of auxiliary inductors presents a clear disadvantage due to the reduced efficiency and power density.

Burst Mode: The second method does not use any extra components but relies on a straightforward switching strategy. When the required output power P_o is lower than the minimum load for soft switching, the converter switches from continuous mode to burst mode. In the burst mode, the converter operates with an output power P_b high enough to enable soft-switching. An example of the burst mode with the corresponding waveforms is shown in Fig. 2(a). The average output power is defined as

$$\langle p_o \rangle = \frac{n}{m} P_b, \quad \forall 1 \leq n \leq m \quad (17)$$

Where n is the amount of switching cycles operating with $p_o = P_b$ and m is the total amount of switching cycles of one burst cycle. The value of P_b depends on the soft-switching region of the converter. When $nT_s < t \leq mT_s$, the output power $p_o = 0$

W, thus the output capacitor delivers the required current to the load, introducing a small voltage ripple. The output voltage ripple can be calculated with

$$\Delta v_o = \frac{I_o \Delta t}{C_o} \quad (18)$$

Where $I_o = \langle p_o \rangle / V_o = n P_b / m V_o$ and $\Delta t = m - n$ ns. This results in

$$\Delta v_o = \frac{n(m-n)P_b}{mV_o C_o f_s} \quad (19)$$

An example of the output voltage ripple with $n \geq 2$ is shown in Fig. 2(b).

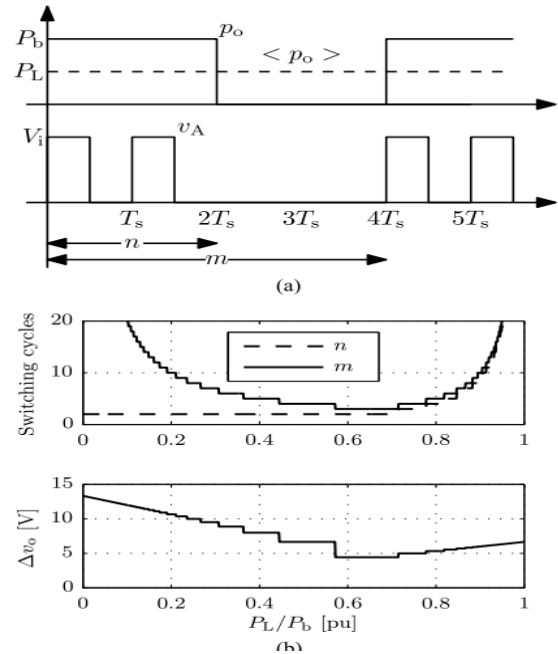


Fig. 2. Burst-mode waveforms. (a) Burst-mode definitions. (b) Output voltage ripple with $n \geq 2$, $P_b = 80$ kW, $V_o = 600$ V, $C_o = 1$ mF, and $f_s = 20$ kHz.

The downside of this method is the need for a larger output capacitance for the same voltage ripple requirements in normal operation without the burst mode. Furthermore, while the switching frequency is unchanged, the converter becomes audible due to the discontinuous operation.

IV. A PHOTOVOLTAIC SYSTEM

A photovoltaic system, converts the light received from the sun into electric energy. In this system, semi conductive materials are used in the construction of solar cells, which transform the self contained energy of photons into electricity, when they are exposed to sun light. The cells are placed in an array that is either fixed or moving to keep tracking the sun in order to generate the maximum power [9]. These systems are environmental friendly without any kind of emission, easy to use, with simple designs and it does not require any other fuel than solar light. On the other hand, they need large spaces and the initial cost is high. PV array are formed by combine no of solar cell in series and in parallel. A simple solar cell equivalent circuit model is shown in fig.3. To enhance the performance or rating no of cell are combine. Solar cell are connected in series to provide greater

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output voltage and combined in parallel to increase the current. Hence a particular PV array is the combination of several PV module connected in series and parallel. A module is the combination of no of solar cells connected in series and parallel. The photovoltaic system converts sunlight directly to electricity without having any disastrous effect on our environment. The basic segment of PV array is PV cell, which is just a simple p-n junction device. The fig.4 manifests the equivalent circuit of PV cell. Equivalent circuit has a current source (photocurrent), a diode parallel to it, a resistor in series describing an internal resistance to the flow of current and a shunt resistance which expresses a leakage current. The current supplied to the load can be given as.

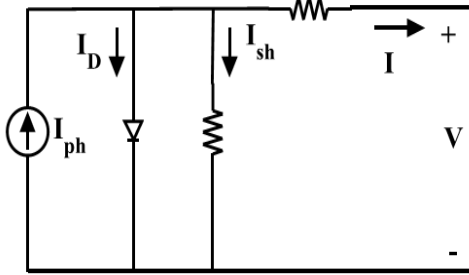


Fig.3. Equivalent circuit of Single diode modal of a solar cell.

$$I = I_{PV} - I_0 \left[\exp\left(\frac{V + IR_s}{aV_T}\right) - 1 \right] - \left(\frac{V + IR_s}{R_p}\right) \quad (20)$$

Where

IPV–Photocurrent current,

IO–diode’s Reverse saturation current,

V–Voltage across the diode,

a– Ideality factor

VT –Thermal voltage

Rs – Series resistance

Rp –Shunt resistance

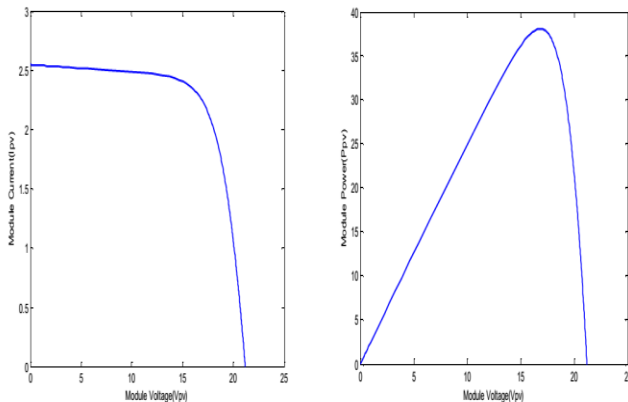


Fig.4. V-I & P-V Characteristics of a 36w PV module.

A single-phase five-level photovoltaic (PV) inverter topology for grid-connected PV systems with a novel pulse width-modulated (PWM) control scheme. Two reference signals identical to each other with an offset equivalent to the

amplitude of the triangular carrier signal were used to generate PWM signals for the switches. A digital proportional-integral current control algorithm is implemented in DSP TMS320F2812 to keep the current injected into the grid sinusoidal and to have high dynamic performance with rapidly changing atmospheric conditions. The inverter offers much less total harmonic distortion and can operate at near-unity power factor. The proposed system is verified through simulation and is implemented in a prototype, and the experimental results are compared with that with the conventional single-phase three-level grid-connected PWM inverter. They range from small residential and commercial rooftop systems to large utility-scale solar power stations. Unlike stand-alone power systems, a grid-connected system rarely includes an integrated battery solution, as they are still very expensive. When conditions are right, the grid-connected PV system supplies the excess power, beyond consumption by the connected load,

Residential, grid-connected rooftop systems which have a capacity more than 10 kilowatts can meet the load of most consumers.^[2] They can feed excess power to the grid where it is consumed by other users. The feedback is done through a meter to monitor power transferred. Photovoltaic wattage may be less than average consumption, in which case the consumer will continue to purchase grid energy, but a lesser amount than previously. If photovoltaic wattage substantially exceeds average consumption, the energy produced by the panels will be much in excess of the demand. In this case, the excess power can yield revenue by selling it to the grid. Depending on their agreement with their local grid energy company, the consumer only needs to pay the cost of electricity consumed less the value of electricity generated. This will be a negative number if more electricity is generated than consumed.^[3] Additionally, in some cases, cash incentives are paid from the grid operator to the consumer.

V. MATLAB/SIMULATION RESULTS

Simulation results of this paper is as shown in bellow Figs.5 to 14.

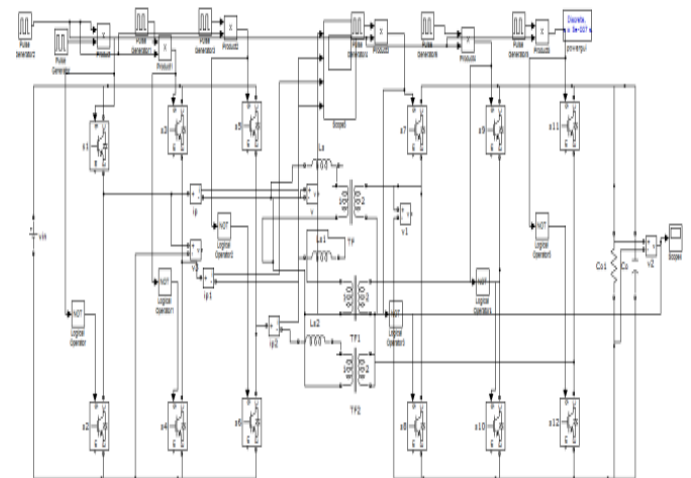


Fig.5. Matlab/simulation conventional circuit of three-phase DAB dc-dc converter Topology.

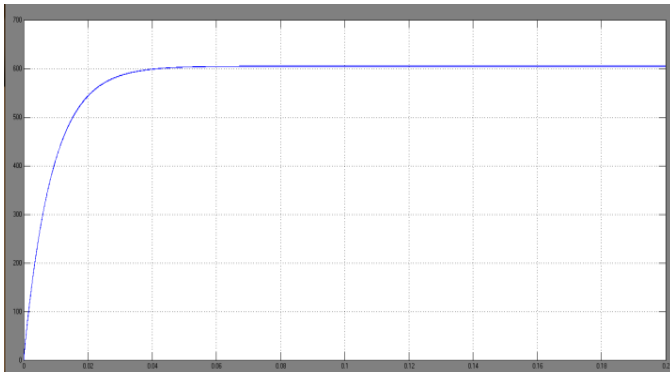


Fig.6. simulation wave form of output voltage.

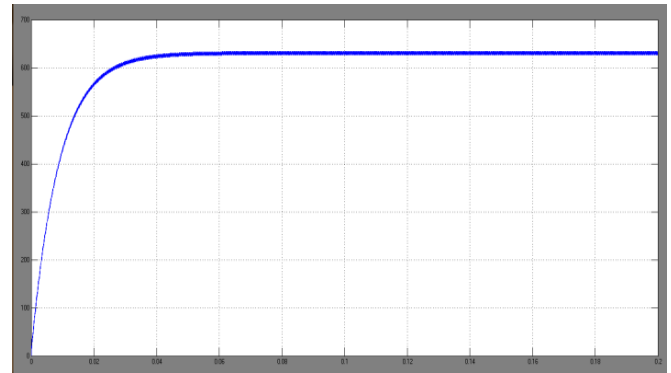


Fig.10. simulation wave form of output voltage.

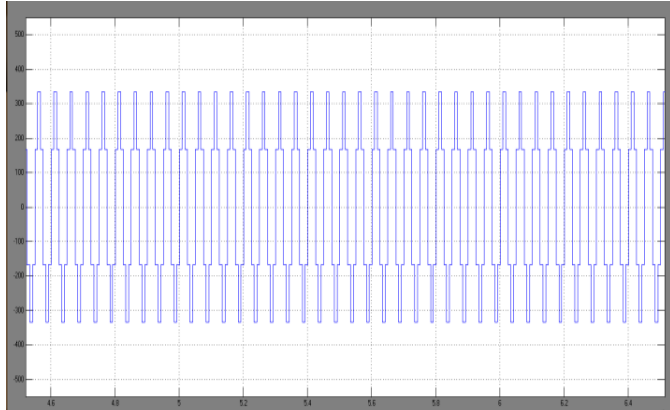


Fig.7. simulation wave form of input line voltage at 750v.

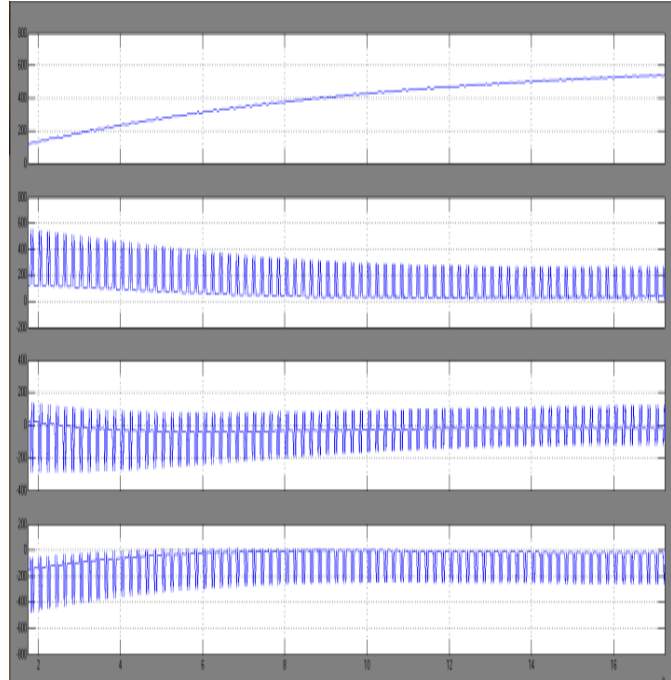


Fig.11. simulation wave form of line voltages and currents.

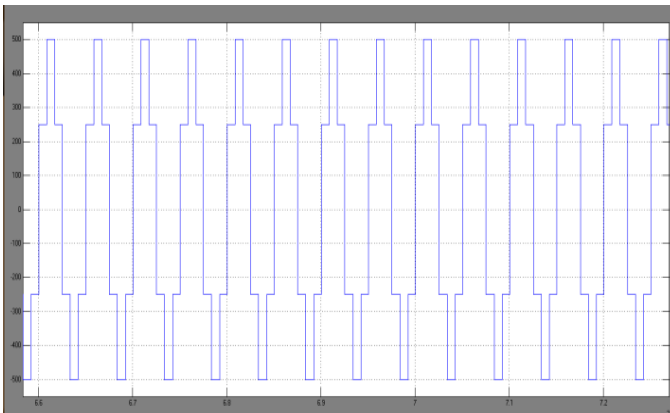


Fig.8. simulation wave form of input line voltage at 750 v.

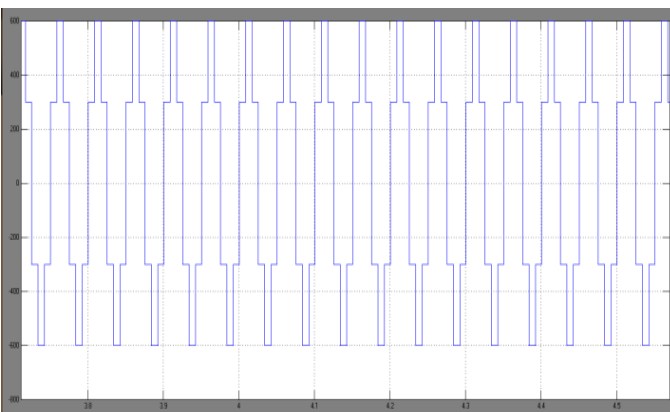


Fig.9. simulation wave form of input line voltage at 900v.

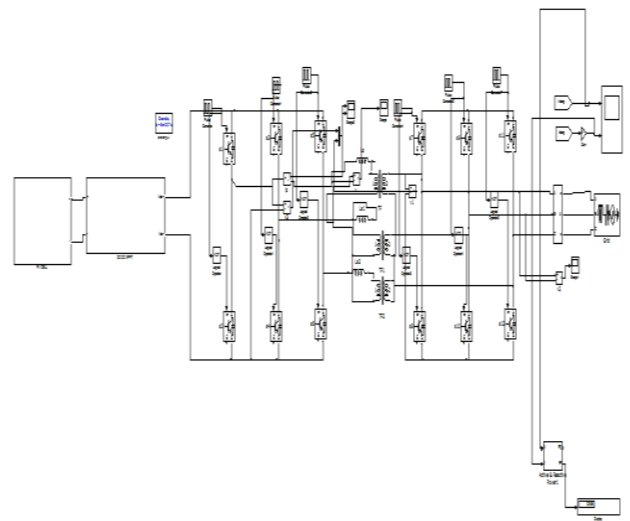


Fig.12. Matlab/simulation proposed method of three-phase DAB dc-dc converter Topology with PV and grid.

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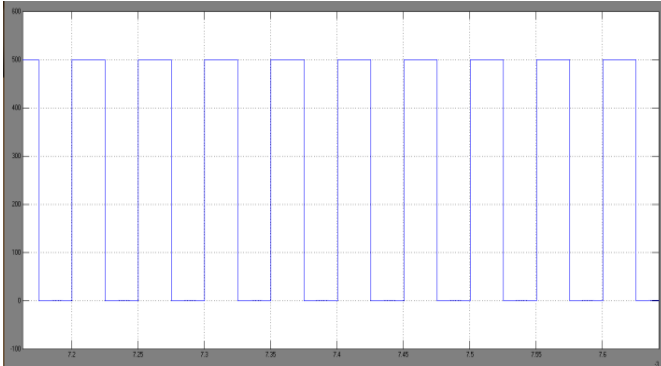


Fig .13.simulation wave form of dc-dc converter Topology with before grid connected output voltage.

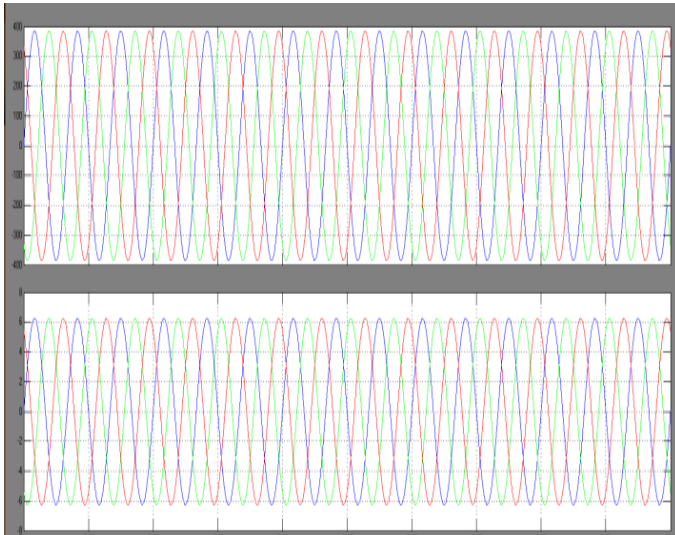


Fig.14. simulation wave form of dc-dc converter Topology with grid connected output voltage and current.

VI. CONCLUSION

This work has evaluated the strategy for utilization of PV Cells for induction motor pumping. The electricity bill gets reduced since solar energy is utilized for agriculture pumping. The Photo Voltaic powered three phase induction motor drive system is successfully designed, modeled and simulated using Matlab/Simulink. The concept of Photo Voltaic grid is proposed. The simulation results of three phase grid connected system for Photo Voltaic pumping are presented. The simulation results are in line with the theoretical results. The scope of this work is the simulation and implementation of three phases PV Powered grid connected system.

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