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Isolated Full Bridge Soft-Switched Three-Port Converter for Satellite Application

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ABSTRACT:A systematic single-stage power conversion method is achieved through a Full Bridge Three-Port DC-DC Converter (TPC) suitable for satellite application. Here, the effective power management is done through the three modes of operation depending on satellite's one orbital cycle since safety margins are the utmost due to merging of multiple energy sources. Also, in order to decouple the multi-inputs and to regulate the output voltage accurately, duty cycle of the power switches and the phase-shift angle between the midpoints of the full bridge are considered as decoupled control variables to allow separate controller design for the three-port converter. Simulation was carried out to validate the effectiveness of the TPC.

KEYWORDS: Three-port converter, phase-shift and duty cycle control, satellite's orbital cycle modes.

I. INTRODUCTION

Sustainable energies have now become the recent trend and the driving force for almost all applications, so as to achieve environment-friendly objectives. However, they are strongly dependent on location and weather conditions, and therefore are intermittent and unpredictable.For this reason, hybridization of multiple energy sources with energy storage units are needed in order to balance the electricity generation and consumption within a power system having a high renewable energy penetration and also in order to ensure reliable and constant power to the load, especially for satellite application where safety margins are the utmost due to merging of multiple energy sources to provide power flows effectively.

To combine several input power sources, two approaches are usually adopted: multiple converter systems and multi-port converter. The advantages of multi-port converter over multiple-converters like reduced component count, enhanced power density, compactness and centralized control. Many topologies are proposed and they can be broadly classified into three groups, non-isolated, fully-isolated and partially-isolated multi-port topologies. Among these, fully-isolated multiple-port converter adopts the magnetic coupling method, where various input power sources can be coupled with transformer windings or independent transformers [1], [2]. Thus, it has been increasingly needed in many applications such as hybrid electric vehicles, fuel cell systems, UPS and photovoltaic systems due to the use of high frequency transformer and galvanic isolation.Therefore, the multi-port converter can be constructed from the basic high frequency switching cells, including the half-bridge (HB), full-bridge (FB), boost-half-bridge (BHB) and their combinations, according to the system constraints imposed by the features of the input power sources. Based upon this principle, a number of three-port (TPC) bidirectional dc-dc converters, which can fully isolate the various power ports and control the power flows into/out of each port [3].

The proposed scheme introduced in this paper is suited for satellite application area. This is derived by replacing the active clamp capacitor in the ZVS circuit with the second voltage source in the ZVS HB inductive dc-dc converter [4], [5]. The rectifier diodes achieve zero-current switching (ZCS) at turn-off avoiding reverse recovery losses. Additionally, the voltage across the diodes is inherently clamped by the output capacitor $C_{o,}$ therefore, voltage rings caused by the stray inductance can be eliminated. Moreover, this converter is superior to its LLC counterparts due to lower complexity of the modulation and control [6]. The operating principleof the proposed system and simulation results are provided to validate the proposed scheme.

II. PRINCIPLE OF OPERATION

The block diagram of the proposed system with power flow regulation and feedback regulators is as shown in Fig.1.

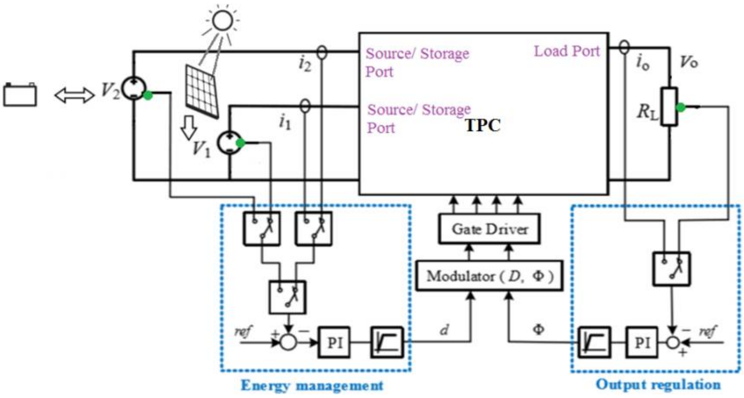


Fig.1 Block diagram of Three-port converter with energy management and output regulation

There are two dc sources, which are connected to TPC and in turn to the load. The TPC converts dc to ac and step-up using transformer and again convert it ac to dc using rectifier. The output power is supply to the DC load. Also soft switching techniques ZVS and ZCS conditions are achieved at the primary and secondary sides of transformer operation without additional circuitry. Four different controllers are designed for the energy management of the renewable power system. At the renewable energy port, either voltage or current can be selected to be regulated depending on the type of theselected renewable energy source. At the energy storage port, constant voltage (CV) and constant current (CI) regulators are implemented, and at the output port, voltage regulation is performed. In order to control the power among the two inputs and the load and thereby balance the power between the different energy sources, two control loops are active at any time. The output port regulation loop is employed to regulate the load voltage by the phase-shift angle Φ. On the other hand, assuming V_1 is the renewable energy source such as fuel cells or photovoltaic, the voltage or current is controlled by the duty cycle D. The power from the other input V_2 as an energy storage unit, for example a battery or a super-capacitor is controlled depending on the power at the renewable energy source and the output load power demand.

Through the phase-shift with duty cycle control, and according to the availability of the renewable energy source and the load demand, the proposed converter can operate in various operating modes (Fig. 2): Dual Input (DI) Mode: When the load demand is higher than the available power from the renewable energy source and the energy storage element delivers the extra energy to the load. Dual Output (DO) Mode: When the input power is higher than the load power demand and the energy storage element balances the power by storing the excess energy. Single Input Single Output (SISO) Mode: When power transfers between the two inputs or from one of the inputs to the output port.

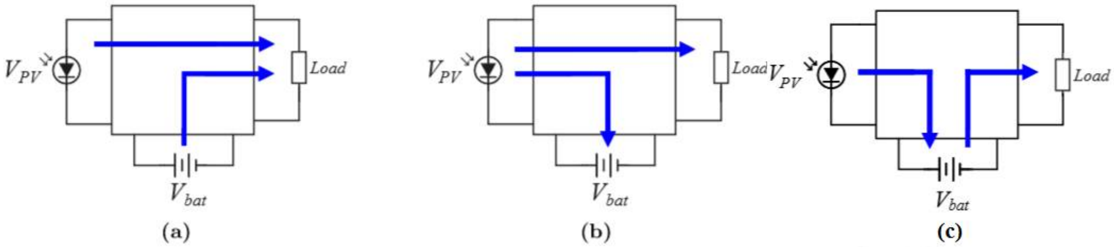


Fig. 2 Operating modes of the proposed converter (a) DI mode (b) DO mode (c) SISO mode

The state-of-charge (SOC) of the energy storage element is always being monitored and when it is above or below its recommended values, the system is set to control the bidirectional port by performing CV or CI control, until the energy storage element SOC allows for a change in the operation mode.

A. Modes of Operation in Satellite's Orbital Cycle

The system has different operational modes in the satellite's one-orbit cycle. Orbital satellite's power platform experiences periods of insolation and eclipse during each orbit cycle, with insolation period being longer. Since MPPT can notably boost solar energy extraction of a photovoltaic (PV) system, the longer insolation period means that MPPT is more often operated to allow a smaller solar array while managing the same amount of load. Two assumptions are made to simplify the analysis: 1) load power is assumed to be constant and 2) battery over discharge is ignored because PV arrays and batteries are typically oversized in satellites to provide safety margins [7].

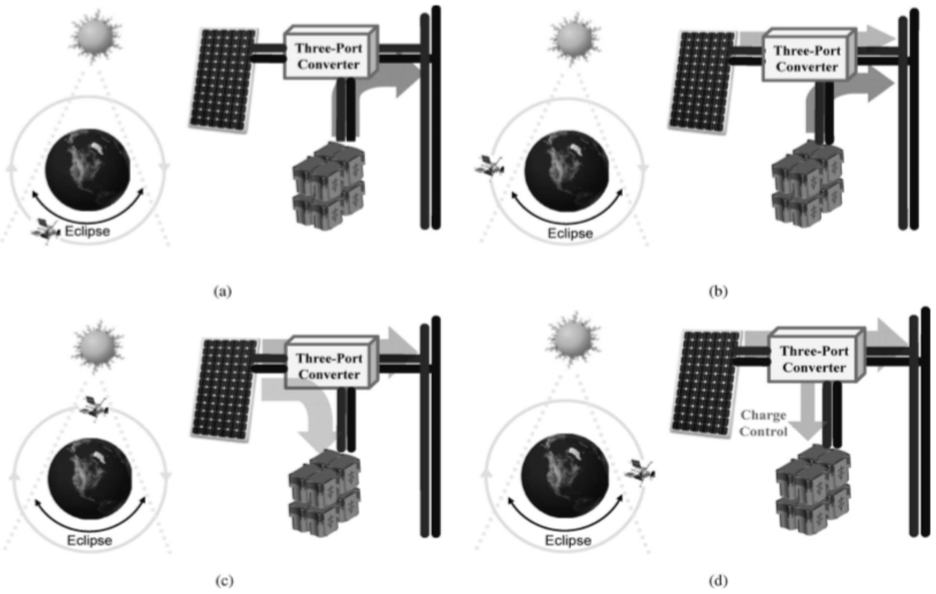


Fig. 3 Different operational modes in satellite's one orbital cycle

Now, the four stages in satellite's one orbit cycle are (Fig.3):
In stage I, battery acts as the exclusive source during eclipse period. In stages II and III, solar power is maximized to decrease battery state of discharge in stage II for initial insolation period, and then to increase battery state of charge in stage III for increased insolation period. In stage IV, battery charge control is applied to prevent battery overcharging and extend battery service life. (a) Stage I operation (eclipse period). (b) Stage II operation (initial insolation). (c) Stage III operation (increased insolation). (d) Stage IV operation (battery charge control).

Therefore, the objective is to regulate different power ports and to provide a decoupling network to allow separate controller designs through decoupling the control variables along with soft switching techniques.

III. PRINCIPLE OF OPERATION

The TPC topology is based on the integration of a Full Bridge switching cell and a bidirectional converter, combined with a high frequency transformer, an ac inductor as the power interface between the primary and the secondary ports, and a bridge rectifier. It has phase-shifted PWM Technique and interleaved boost converter.

A. Circuit Description

Fig. 4 shows the schematic of the proposed TPC topology, where the renewable energy source is connected to the input port V_1, the energy storage element to the bidirectional port V_2, and the output port interfaces with a dc-ac inverter connected to the grid.

It consists of two input inductors, L_1 and L_2, an ac inductor L_{ac}, four power MOSFETs $M_1 \sim M_4$, and a high frequency transformer with a turn ratio of 1: n. The ac inductor, which is the sum of the leakage inductance and the auxiliary inductance, is the power interface element between primaryand secondary sides of the transformer. Switches M_1, M_2 and M_3, M_4 are driven with complementary gate signals with a deadband. i_{L1} and i_{L2} are defined as the input inductor currents; V_{ab} is the voltage between the midpoints of the bidirectional interleaved boost switching legs, and i_{Lac} is the current of the secondary side winding [8], [10].

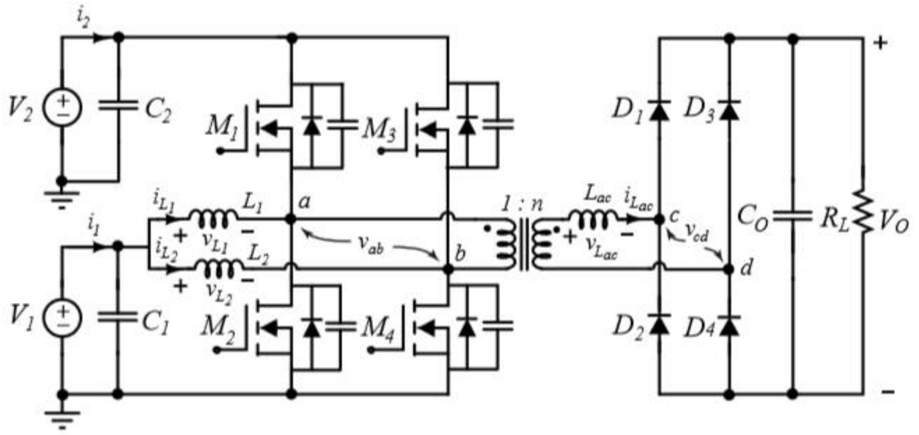


Fig. 4 Topology of the proposed TPC

In order to decouple the two inputs, V_1 and V_2, and regulate the output voltage accurately, both the duty cycle (D) and the phase-shift angle (Φ) are adopted as the control variables simultaneously. The duty cycle of the power switches is used to adjust the power among the two independent sources, and the phase-shift angle between the midpoints of the full bridge is employed to regulate the power flow to the output port.

Duty cycle plus phase-shift control mode

Switches M_1 and M_2 are turned on and both of the inputs can deliver power to the load. In order to decouple the two inputs effectively as well as regulate the output voltage accurately, both the duty cycle and the phase-shift angle are used as the control variable. Therefore, the power flowing between the inputs and the power delivered to the load are controlled by D and Φ, respectively (Fig. 5).

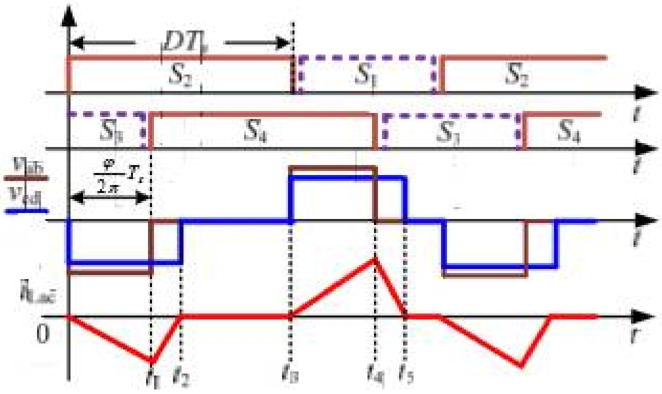


Fig. 5 Operating waveforms in duty cycle plus phase-shift control mode

Completely demagnetized operation is the preferred mode since the output port voltage only depends on the phase-shift value, as shown in (1), for $\Phi < \min[D, (1-D)]$. Therefore, in completely demagnetized operation mode, the energy transferred to the output does not depend on the converter duty cycle [9].

$$V_o = \frac{nV_2}{k}.\Phi\left(-\Phi + \sqrt{\Phi^2 + 2k}\right) \tag{1}$$

where

$$k = \frac{2L_{ac}}{R_L T}$$

The relationship between V_1 and $V_2$is obtained as

$$V_2 = \frac{V_1}{(1-D)} \tag{2}$$

Therefore, in the completely demagnetized operating mode the power flow from V_1 and V_2 to the output port will be entirely controlled by Φ.

IV. SIMULATION TEST RESULTS (MATLAB/ SIMULINK)

The feasibility of the proposed system is investigated for orbital satellite application, which is mostly used for obtaining a discrete precise positioning of objects with high resolution. For such an application, stepper motors can be used to attain it which has the advantages of providing precise positioning with each command electrical pulse input, speed control due to the precise increments of movement also allows excellent control of rotational speed, and maximum torque at low speeds, so they are a good choice for applications requiring low speed with high precision.

For closed loop simulation model, we have chosen V_1 and V_o as the controlling parameters. PI controller is used for tuning the duty cycle value. First we have sensed V_1 (a renewable energy source) and compared it with the reference value (50V). An error signal is obtained, which is fed to the PI controller. The output of the PI controller is the duty cycle. Thus the obtained duty cycle value is compared with triangular generator without a phase shift and the obtained pulses are fed into first leg of the Full Bridge (FB) converter.

Similarly, V_o is sensed and compared with reference value (350V) to obtain an error signal. Thus the obtained duty cycle value from PI controller is compared with triangular generator with a phase shift of 90^o and the obtained pulses are fed into second leg of the FB converter.

The closed loop configuration is as shown in Fig. 6. The modes of operation can be obtained when the constant input voltages are replaced by solar and battery source. The reference values of the output voltage can be changed from 200to 350V. The output voltage is obtained around 380V and an output current of 1 A. ZVS and ZCS conditions at turn on and turn off periods respectively were obtained for the MOSFETs.

System Parameters	Specification
Input voltage V_1	50V
Input voltage V_2	100V
Output voltage V_o	380V
Inductors L_1 and L_2	760µH
Transformer	Linear transformer with 1 : 4 ratio
Capacitor C_1	20µF
Capacitor C_2	66 µF
Capacitor C_o	20µF
AC Inductor L_{ac}	0.001mH
Switching frequency f_s	60kHz
Load	Hybrid Stepper Motor with load torque of 0Nm (for Orbital Satellite application)

TABLE I. SYSTEM SPECIFICATIONS OF TPC CONVERTER

Simulink model motor input parameters are: phase voltage (A+, A- , B+ and B-) and mechanical load– T_L and output parameters from motor model are: phase current– I_{ph}, electromagnetic torque– T_e, and rotor speed– w and rotor position– theta. Electrical part or motor control circuit is consisted of three functions entities: control block, hysteresis comparator and MOSFET PWM converter.

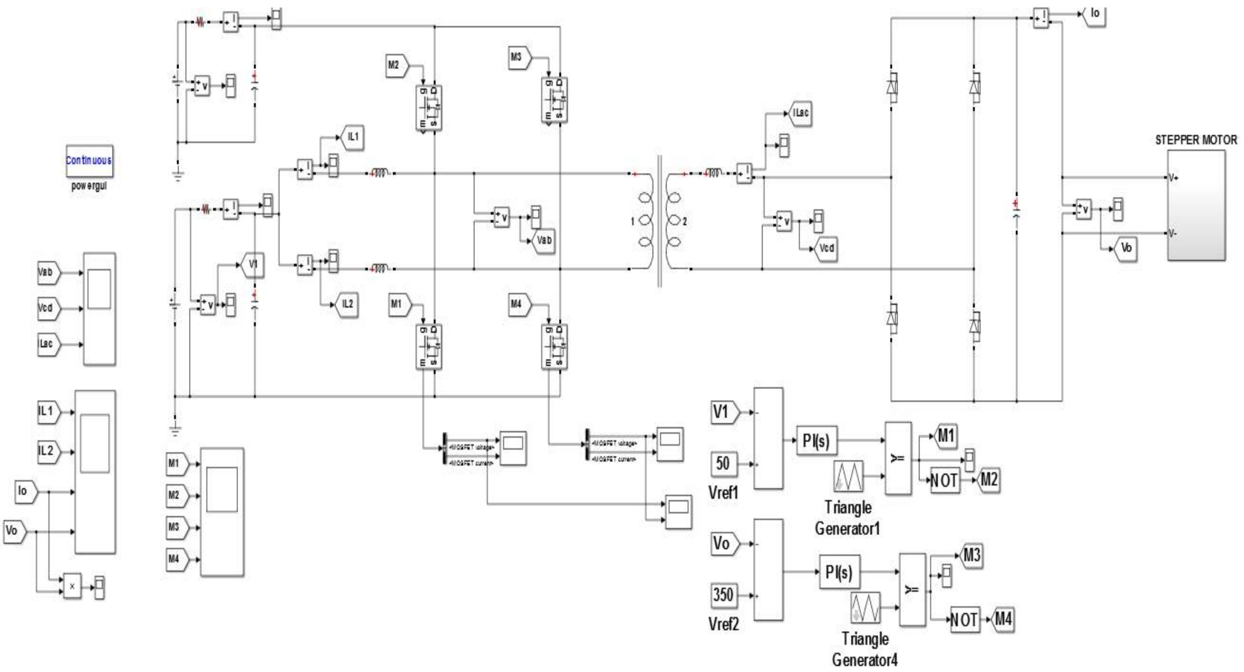
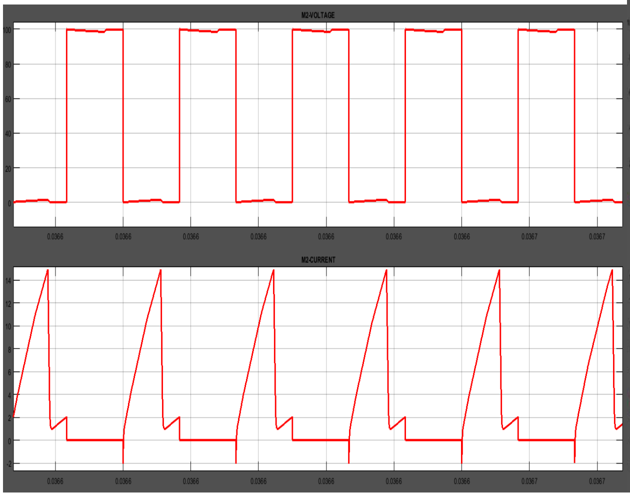


Fig. 6 Closed loop Simulink model of TPC with hybrid stepper motor as load with a load torque of 0 Nm

The ZCS and ZVS conditions of the switches are in Fig.7 and Fig. 8.



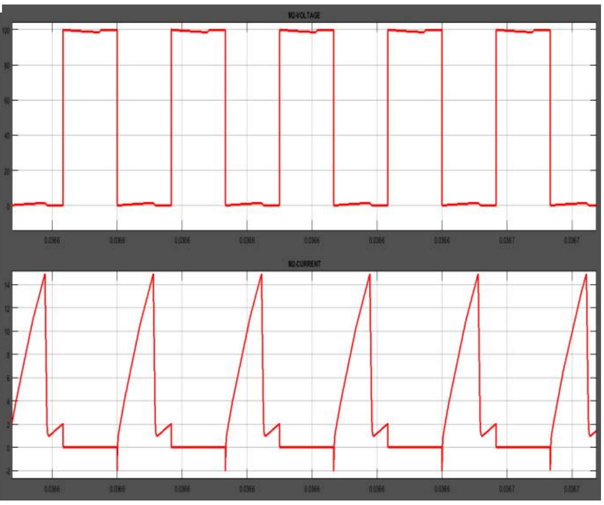


Fig. 7ZCS condition of TPC

Fig. 8 ZVS condition of TPC

Fig. 7 represents ZCS condition of the switch in which the MOSFET gets turned off at zero current. Hence, it eliminates the switching loss caused by MOSFET current tailing and by stray inductances. It is used to commutate SCR's. In Fig. 8, the voltage falls to zero before the MOSFET is turned on, this is the ZVS condition of the switch. Thus, eliminating any overlap between voltage and current and thus minimizing losses.

The motor transient performance characteristics for load of 0 Nm are given by Fig. 9.

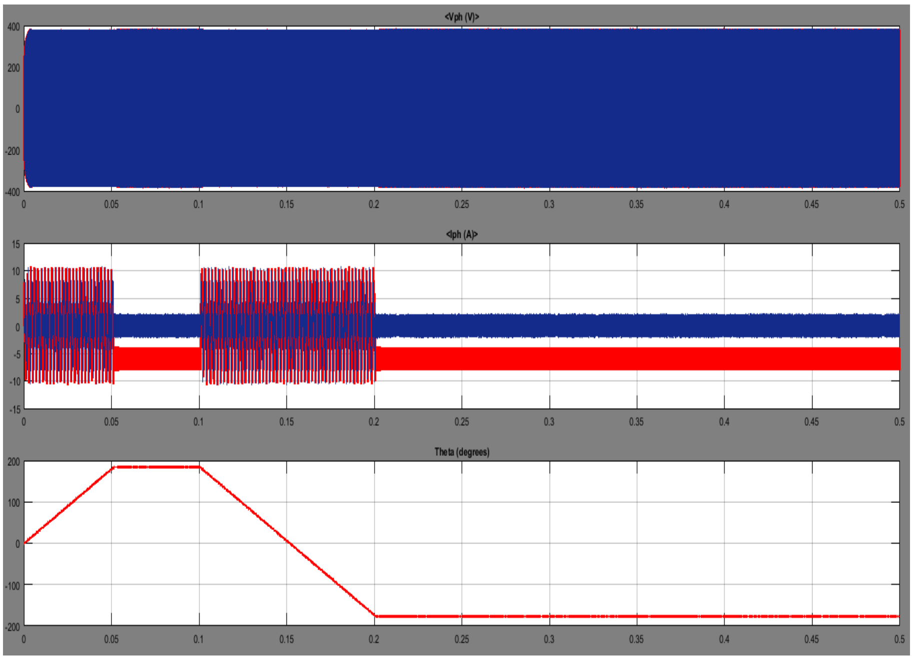


Fig. 9 Motor transient performance characteristics for load of 0Nm

The phase voltage V_{ph} (V), phase current I_{ph} (A) and rotor position theta (degrees) are considered as the motor characteristics. The accuracy of the stepper positioning is measured through the theta. The clockwise and counter clockwise rotation depends on the direction signal given to the stepper, which in turn controls the solar panel rotation in case of satellite operation. The phase shifted PWM pulses with a duty cycle D which is given to the MOSFETs M_1 through M_4. The MOSFETs M_1 and M_4; and M_2 and M_3 are driven with complementary gate signals with deadband. In order to decouple the two inputs, V_1 and V_2, and regulate the output voltage accurately, both the duty cycle and the phase-shift angle are adopted as the control variables simultaneously. Soft switching technique is inherently possible without an additional circuitry. The circuit itself behaves as a series-parallel resonant LLC converter to provide ZVS and ZCS conditions.The output voltage V_o of 380V is obtained at the output with a small ripple voltage (Fig. 10). The average voltage is a pure high voltage DC.

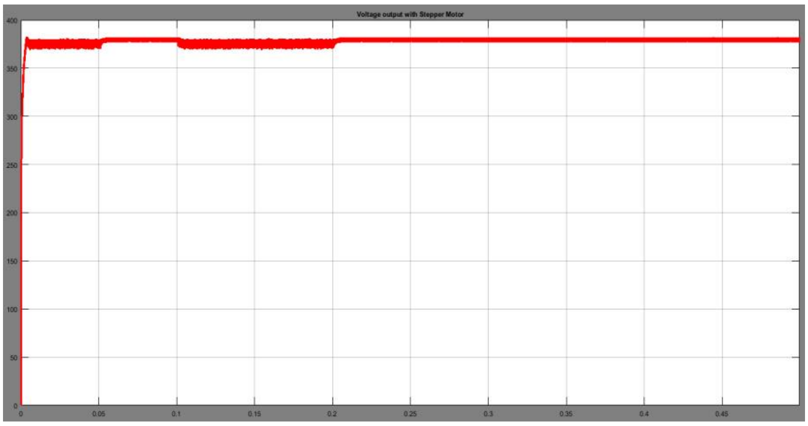


Fig. 10 Output voltage V_o of closed loop model TPC with ripple voltage content

V. CONCLUSION

A Three port isolated dc-dc converter suitable for satellite application is proposed based on duty cycle and phase-shift control for hybrid renewable energy systems with energy storage unit as renewable energy alone is less efficient due to its intermittent nature. A detailed simulation for the proposed TPC with fixed input voltages in closed loop condition with hybrid stepper motor load was obtained. The main objective of the proposed system is to investigate its feasibility in orbital satellite operation which is mainly used for precise positioning since safety margins are utmost in order to provide power flow effectively. The motor performance characteristics comprising theta showing the accuracy of positioning were obtained with a load torque 0Nm and zero voltage switching and zero current switching techniques were also evaluated without any additional circuitry.

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