



# Innovative Science and Technology Publications

**International Journal of Future Innovative Science and Technology**  
**ISSN: 2454- 194X** **Volume - 2, Issue - 2**



Manuscript Title

## Asymmetrical PWM Plus Phase Shift Control of Triple Port Isolated Bidirectional DC-DC Converter Interfacing Battery and Supercapacitor

***K.Shreelekha, S.Arulmozhi***

*(M.E Student): Dept. of EEE, (Assistant Professor): Dept. of EEE,  
Sri Venkateswara College of Engineering, Sriperumbudur, India.*

*E-Mail: [shreek71192@gmail.com](mailto:shreek71192@gmail.com), [arulmozhi@svce.ac.in](mailto:arulmozhi@svce.ac.in)*

**May – 2016**

**[www.istpublications.com](http://www.istpublications.com)**

# Asymmetrical PWM Plus Phase Shift Control of Triple Port Isolated Bidirectional DC-DC Converter Interfacing Battery and Supercapacitor

**K.Shreelekha, S.Arulmozhi**

(M.E Student): Dept. of EEE, (Assistant Professor): Dept. of EEE,  
Sri Venkateswara College of Engineering, Sriperumbudur, India.

E-Mail: [shreek71192@gmail.com](mailto:shreek71192@gmail.com), [arulmozhi@svce.ac.in](mailto:arulmozhi@svce.ac.in)

## ABSTRACT

This paper emphasis on the triple port full bridge isolated bidirectional dc-dc converter using asymmetrical pulse width modulation plus phase shift control technique. In this proposed topology all the three ports are voltage fed ports in which battery is used as main energy storage and supercapacitor is interfaced as a secondary energy storage to solve some problems of battery and to improve the working conditions of the hybrid energy storage system. Interfacing of battery and supercapacitor mainly leads to stress reduction of battery. Since the source ports are fed by battery and supercapacitor which has a wide input voltage range asymmetrical pulse width modulation plus phase shift control technique is implemented for this topology. The drawbacks of phase shift control technique such as secondary side voltage overshoot occurs due to the voltage mismatch between the input and output side of the ports is overcome in this proposed control technique. With this control technique the duty cycle of the source port switches alone is varied and the duty cycle of the load port switches is kept constant. The proposed control technique has the advantage of reduced current stress, rms value of currents and wide zero voltage switching (ZVS) range. In addition a control scheme employing proportional plus integral (PI) regulator is employed. The simulation results for different operating modes are carried out using MATLAB/Simulink 2014 environment to verify the effectiveness of the proposed converter.

**Keywords**—Hybrid energy storage system (HESS); bidirectional dc-dc converter (BDC); battery; supercapacitor; energy storage system (ESS);; phase shift (PS); pulse width modulation plus phase shift (PWMPS)

## I. INTRODUCTION

The Bidirectional DC - DC converters (BDCs) serves the purpose of stepping up or stepping down the voltage level between its input and output along with the capability of power flow in both the directions. BDCs can be classified into isolated and non-isolated types. Galvanic isolation between multi-source systems is a requirement mandated by many standards. Voltage matching in case of large voltage ratios between two sources, personnel safety, noise reduction, interference blocking capability and correct operation of protection systems are the main reasons behind galvanic isolation which is required by many sensitive DC loads. Common

IBDC topology is Dual Active Bridge (DAB) topology in which full bridge voltage fed converters are used at both the ends of the isolation transformer. In order to interface multiple renewable energy sources or to interface multiple energy storage systems with the load; multiport isolated bidirectional dc-dc converters are finding their increasing applications. Hybrid Energy Storage System (HESS) – battery and supercapacitor combination are finding their promising application in hybrid and fuel cell powered Electric Vehicles (EV) , smart grid, large scale wind and photovoltaic systems , Uninterruptible Power Supplies (UPS) etc [8]. The optimum choice of construction for this type of HESS is triple active full bridge (TAB) topology [7],[8],[9] which is derived

from dual active bridge (DAB) topology [1].

Three port triple half bridge bidirectional dc-dc converter is presented in [5] that interfaces supercapacitor, fuel cell and load using pulse width modulation plus phase shift control technique (PWMPS). With this control technique the drawbacks of conventional phase shift control such as voltage mismatch between the input and output side of the ports is overcome. However it has only bidirectional port hence it does not support regenerative load.

Three port current fed full bridge bidirectional converter which has the advantage of reduced current ripple at the input due to the presence of input inductor is presented in [7] but the drawback is that it is suitable only for low power and low output voltage applications. Though the filter requirements are less it increases the control complexity of the circuit.

A series resonant three port converter with load side diode bridge is presented in [8] in which all the ports are voltage fed ports. ZVS is possible in this converter such that switching loss reduces. But the drawback of this converter is ZVS is not possible for load side port and not suitable for regenerative load.

In phase shift control technique when the amplitude of the equivalent input voltage of port does not match with that of the

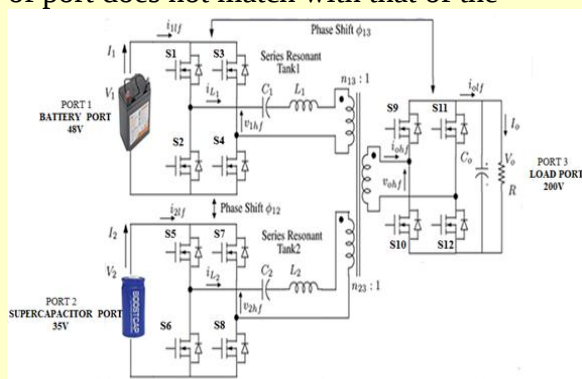


Fig. 1. Multiport isolated bidirectional dc-dc converter

equivalent output voltage of that port then the current stress increases and rms value of currents also become higher and the reactive power transferred also increases, which leads to high conduction losses. Thus ZVS cannot be achieved in light load condition. So in order to overcome this voltage mismatch between the input and the output side of the ports, PWM plus phase shift control is presented in [3].

Asymmetrical duty cycle control for triple half bridge topology is presented in [12]. In this control technique the phase shift is used for the power flow control and the duty cycle of half bridge in every port is different and adjustable based on its own input voltage so wider ZVS range is obtained. This control technique is suitable where there is wide variation in input voltage.

In order to overcome the drawbacks of phase shift control technique and triple active half bridge configuration, a series resonant triple active full bridge topology [9] is proposed in this paper in which all the ports are voltage fed ports that interfaces battery which acts as primary storage and supercapacitor which acts as transient storage with asymmetrical PWM plus phase shift control in which in addition to phase shift control the duty cycle port switches is varied.

## II. PROPOSED TRIPLE ACTIVE BRIDGE CONVERTER

### A. Circuit Construction

The proposed triple active bridge bidirectional dc-dc converter circuit consists of three active full bridges, three winding transformer and two series resonant tanks formed by  $L_1, C_1$  and  $L_2, C_2$ . Port 1 is fed by battery port and port 2 is fed by supercapacitor. Port 3 is load port (Resistive

load and DC motor load). Each port consists of full bridge circuit with four switches. The switches are realized using MOSFET enabling bidirectional current flow in all the ports. The three winding transformer is mostly a step-up transformer. It has three functions (1) combines input DC sources in magnetic form, (2) provides electrical isolation, (3) step up voltage from Low Voltage Side(LVS) to High Voltage Side (HVS). 4) leakage inductance acts as energy transfer elements. The converter is operated at constant switching frequency  $F_s$  above the resonant frequency  $F_r$ .

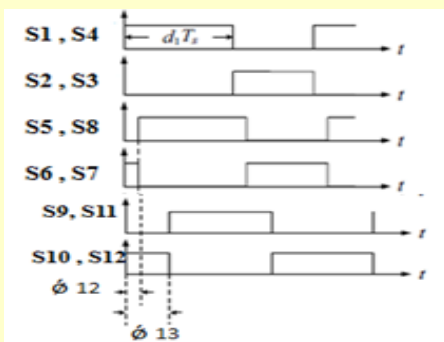


Fig. 2. Idealized key switching waveform for asymmetrical PWM plus phase shift control

### B. Asymmetrical PWM plus phase shift control technique

In this control technique the duty cycle of the switches and also phase shift between the bridges are varied. This PWM control of duty cycle acts as electric transformer between the equivalent input voltage and the equivalent output voltage, so that both positive and negative amplitudes of equivalent input voltages  $V_1$  and  $V_2$  are equal to the positive and negative amplitudes of equivalent output voltage  $V_{1hf}$  and  $V_{2hf}$ .

In asymmetrical duty cycle control the duty cycle of the switches of input ports alone are varied whereas the duty cycle of the switches of load port is kept constant 50% Duty cycle (D). The positive conduction switches of input ports (M1,M4 ; M5,M8) are controlled with duty cycle D ( $D < 0.5$ ) and the negative conduction switches (M2,M4 ; M6,M7) of input ports are controlled with duty cycle  $(1 - D)$  ( $D > 0.5$ ).

The switches of load port (M9,M12) and (M10,M11) are controlled complementarily with fixed duty cycle of ( $D = 0.5$ ). since both the port 1 and port 2 (voltage fed port ) which is fed by battery and supercapacitor has a wide variation in input voltage this type of control is more suitable compared to symmetrical duty cycle control. In the general the switches of the load port are controlled with fixed duty cycle. The idealized key switching waveform for asymmetrical PWM plus phase shift control technique is shown below .

### III. MODES OF OPERATION

The operation of the proposed TAB converter is based on the two major constraints.

- 1) When the port supplies power to the load i.e when the port acts as source it acts as inverter . (discharging mode).
- 2) when the port sinks power i.e charging mode it acts as rectifier.

The requirements on the region of operation are as follows

- 1) To supply the load power independently from each of the sources and share the load between the sources

- 2) At reduced load , the main energy storage is to supply the load and charge the supercapacitor.

3) When the load is regenerative this power is used to charge the battery and supercapacitor.

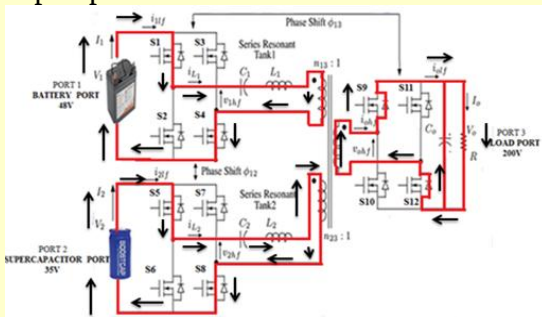


Fig. 3. Forward mode circuit diagram

#### A. Forward mode

In forward mode both port1-battery port and and port2- supercapacitor port supplies the load port such that both the battery port and supercapacitor port is in discharging mode. control technique implemented is asymmetrical PWM plus phase shift control technique. Here with this technique the both the phase shift and duty cycle of the switches are controlled. There is no phase shift between port 1 and port 2 is and between port 1 and port 3 is  $65.5^\circ$ . The duty cycle for the port-1 switches S1, S3 is less than 0.5 and for S2, S4 it is varied greater than 0.5. Port 1 acts as inverter since it supplies power. MOSFET switches M1, M4 for positive mode or M2, M3 for negative mode conducts. Port 1 acts as inverter since it supplies power. MOSFET switches M1, M4 for positive mode or M2, M3 for negative mode conducts. The duty cycle for the port-2 switches S5, S8 and S6, S7 is varied. Port 2 acts as inverter. MOSFET switches M5, M8 for positive mode or M6, M7 for negative mode conducts. The duty cycle of the switches of port 3 i.e. load port is kept constant 0.5 due to wide variation in input voltage. Port 3 acts as rectifier since it sinks power. Antiparallel diodes of MOSFET

switches comes into action by the process of synchronous rectification. Antiparallel diode D9, D12 conducts for positive mode or the antiparallel diode D10, D11 conducts for negative mode of operation. Port 1, port 2 and port 3 power is positive when the converter operates at mode 1.

#### B. Regenerative mode

In regenerative mode port 1 and 2 are charged by the regenerative load i.e DC – motor load. Power is fed from the regenerative load when the generated emf is greater than the terminal voltage. This power flows in the reverse direction through port 3 to the port 1 and port 2 thereby battery and supercapacitor will be getting charged by the regenerative load. The phase shift between port 1 and port 2  $\phi_{12}$  is  $64.5^\circ$ . There is no phase shift between port1 and port 3  $\phi_{13}$ . The duty cycle for the port-1 switches S1, S3 is less than 0.5 and for S2, S4 it is varied greater than 0.5. Port 1 acts as rectifier since it sinks power. Antiparallel diodes of MOSFET switches comes into action when the port acts as rectifier. Antiparallel diode D1, D4 conducts for positive mode or antiparallel diode D2, D3 conducts for negative mode. The duty cycle for the port-2 switches

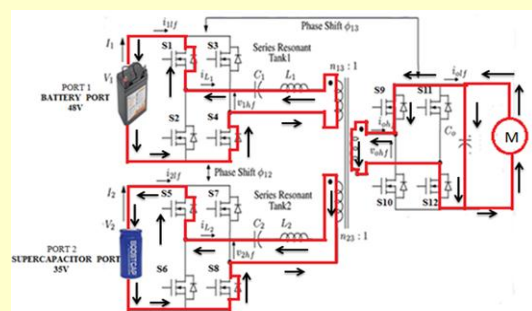


Fig. 4. Regenerative mode circuit diagram

S5,S6,S7,S8 is kept constant of the value of 0.5. Port 2 acts as rectifier since it sinks power. Antiparallel diodes of MOSFET switches comes into action. Antiparallel diodes D5, D8 conducts for positive mode or antiparallel diodes D6, D7 conducts for negative mode of operation. The duty cycle for the port-3 switches S9, S11 and for S10, S12 it is varied. Port 3 acts as inverter since it supplies power ; MOSFET switches M9, M12 conducts for positive mode or the MOSFET switches M10, M11 conducts for negative mode of operation.

#### IV. ANALYSIS AND DESIGN

##### A. Converter design and analysis

For the design of the proposed triple port converter converter the frequency factor of 1.1 is chosen and the quality factor of 4 is chosen [2] for the design purpose and it is calculated from the following equations.

$$\text{Frequency ratio} = \frac{w_s}{w_i} = \frac{2 * \pi * f_s}{\frac{1}{\sqrt{L_i C_i}}} \quad (1)$$

$$\text{Quality factor } Q_i = \frac{Z_i}{\frac{8 * R * n_{i3}}{\pi^2}} \quad (2)$$

$$\text{Impedance } Z_i = \sqrt{\frac{L_i}{C_i}} ; \text{ where } i = ,2 \quad (3)$$

The inductor values for series resonant tank is calculated from the following equation [6] and the value of capacitor is chosen such that frequency factor is 1.1.

$$L_i = \frac{V_i * V_i * T}{162 * P} \quad i = 1,2 \quad (4)$$

where T is the time period and P is the output power in watts.

The output voltage , current and power is calculated from the following equation.

$$\frac{\frac{V_1}{n_{13}} * \sin \phi_{13}}{Q_1 (F_1 - \frac{1}{F_1})} + \frac{\frac{V_2}{n_{12}} * \sin(\phi_{12} - \phi_{13})}{Q_2 (F_2 - \frac{1}{F_2})} \quad (5)$$

$$V_o =$$

$$I_o = \frac{8}{\pi^2} * \frac{n_{13} * \sin \phi_{13}}{Z_1 (F_1 - \frac{1}{F_1})} + \frac{8}{\pi^2} * \frac{n_{12} * \sin(\phi_{13} - \phi_{12})}{Z_2 (F_2 - \frac{1}{F_2})} \quad (6)$$

If the load is resistive load then output power is calculated as  $P_o = I_o * I_o * R$  (7)

The range of phase shift for this technique depends on the D. where D is the Duty cycle of the switches. In order to limit the rms and peak current through the transformer [4] when operating at a small or large duty cycle, the maximum and minimum limiting duty cycles are set to be  $D_{\max} = >0.5$  and  $D_{\min} = <0.5$

$$\phi_{\max} = \min(D\pi, D(1 - \pi)) \quad (8)$$

##### B. Modeling of supercapacitor

Supercapacitor bank of 35 volt is modeled by connecting 13 supercapacitor cells each of 2.7 volt are connected in series  $N_s$ .

$$\begin{aligned} V_{\max} &= 35 \text{ Volts} \\ N_s &= \frac{V_{\max}}{V_{\text{cell}}} = \frac{35}{2.7} \end{aligned} \quad (9)$$

$$N_s = 13 \text{ cells}$$

In order to increase the net equivalent capacitance of the supercapacitor bank 14 cells are connected in parallel. [11].

$N_p = 14$  cells The total of 182 cells is used to model a supercapacitor bank of 35 volts.

$$N_T = N_p * N_s \quad (10)$$

$$N_T = 13 * 14 = 182 \text{ cells}$$

Lead acid battery of 48 volt with 12 ampere hour rating is modeled to act as dc source for port 1.

TABLE III. CONVERTER DESIGN SPECIFICATIONS

| PARAMETERS                                     | VALUES        |
|------------------------------------------------|---------------|
| Port 1-Battery port input voltage $V_1$        | 48 Volts      |
| Port 2-Supercapacitor port input voltage $V_2$ | 35 Volts      |
| Port 3- Load port output voltage $V_o$         | 200 Volts     |
| Switching frequency $f_s$                      | 100 KHZ       |
| Turns ratio between port 1 and 3 $n_{13}$      | 0.24          |
| Turns ratio between port 2 and 3 $n_{23}$      | 0.18          |
| Inductance of series resonant tank 1 $L_1$     | 28.44 $\mu$ H |
| Inductance of series resonant tank 2 $L_2$     | 15 $\mu$ H    |
| Capacitance of series resonant tank 1 $C_1$    | 0.1 $\mu$ F   |
| Capacitance of series resonant tank 2 $C_2$    | 0.22 $\mu$ F  |
| Output Current $I_o$                           | 2.5 A         |
| Output Power $P_o$                             | 500 Watts     |
| Resistance R                                   | 80 $\Omega$   |

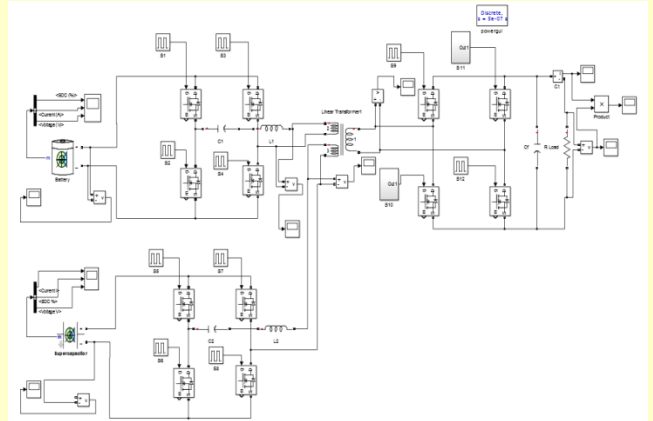


Fig. 5. Simulation diagram of triple port isolated bidirectional dc-dc converter

TABLE IV. SUPERCAPACITOR CELL SPECIFICATIONS

| PARAMETERS                                           | VALUES          |
|------------------------------------------------------|-----------------|
| Equivalent capacitance of the Supercapacitor cell    | 50 Farads       |
| Voltage rating of the Supercapacitor cell $V_{cell}$ | 2.7 Volts       |
| Equivalent DC Series Resistance ESR                  | 20 m $\Omega$   |
| Maximum surge voltage of a cell                      | 2.85 Volts      |
| Maximum leakage current                              | 0.075 mA        |
| Operating temperature                                | 25 $^{\circ}$ C |

TABLE V. BATTERY DESIGN SPECIFICATIONS

| PARAMETERS              | VALUES   |
|-------------------------|----------|
| Battery voltage         | 48 Volts |
| Ampere – hour rating    | 12 Ah    |
| Initial state of charge | 90 %     |

## V. SIMULATION RESULTS

### A. Open loop simulation results

In Fig 5 the simulation circuit diagram of multiport isolated bidirectional dc-dc converter is shown with battery as input for port 1 of 48 V and supercapacitor as a input for port 2 of 35 V and port 3 is the load port ( R- load for forward mode and DC motor load for regenerative mode) of 200 V. All the three ports are active bridges the switches are realized using MOSFETS.

Simulation result for forward mode of operation of the converter is shown such that both battery and supercapacitor supplies the resistive load. So as shown in fig. 14,15 the state of charge of both battery and supercapacitor decreasing from its initial values. Voltage mismatch between the input and output side of the ports is overcome which is the major significance of this technique as shown in fig. 12,13 and fig. 16,17. In fig. 6,7,8,9,10,11, X-axis represents voltage in volts and Y-axis represents time in  $10^{-4}$  seconds.

Simulation result regenerative mode is shown in which both battery and supercapacitor is charged by the DC – motor load which acts as DC - generator in regenerative operation. In

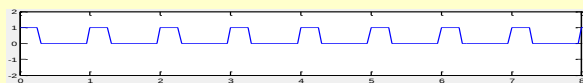


Fig. 6. Gating signal for switches S1,S5

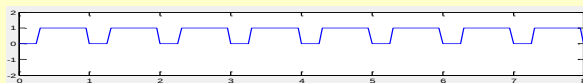


Fig. 7. Gating signal for switches S2, S6

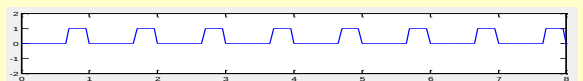


Fig. 8. Gating signal for switches S3, S7

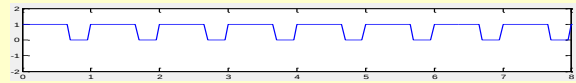


Fig. 9. Gating signal for switches S4, S8

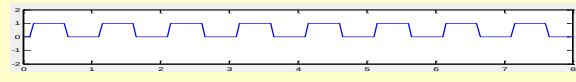


Fig. 10. Gating signal for switches S9, S12

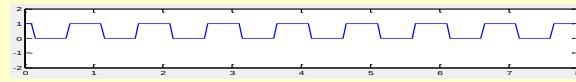


Fig. 11. Gating signal for switches S10, S11

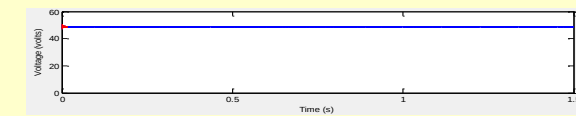


Fig. 12. Port 1 - Battery port input voltage

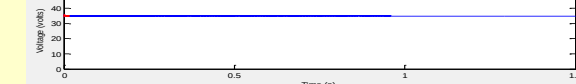


Fig. 13. Port 2 - Supercapacitor port input voltage

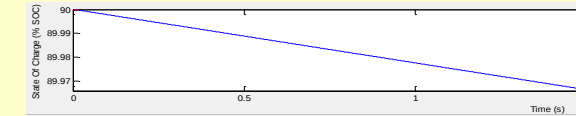


Fig. 14. Port 1 – Battery state of charge

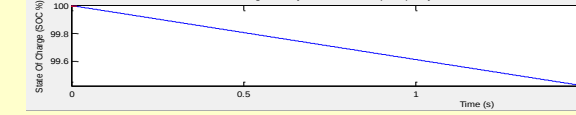


Fig. 15. Port 2 – Supercapacitor state of charge

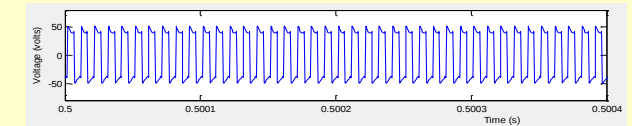


Fig.16. Port 1 output voltage – Transformer primary winding 1 voltage

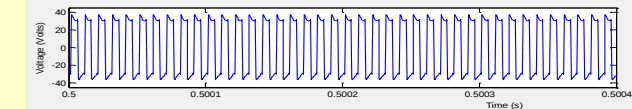


Fig.17. Port 2 output voltage – Transformer primary winding 2 voltage

regenerative mode the torque is negative of -42 N-m and the speed is positive of 16 rad/sec as shown in fig. 25 and 26. The state of charge of both battery and supercapacitor is increasing as shown in fig. 17 and 18. In fig. 17,18,19,20,21,22, X-axis.

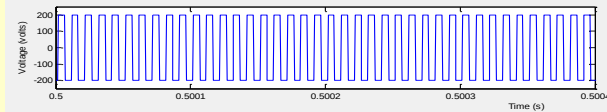


Fig.18. Port 3 input voltage – Transformer secondary winding voltage

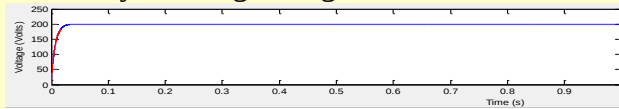


Fig. 19. Port 3 – Load port output voltage

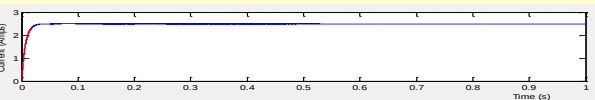


Fig. 20. Port 3 – Load port output current

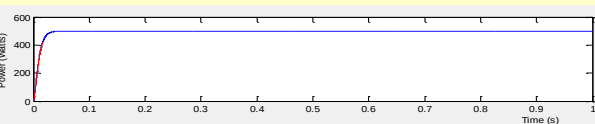


Fig. 21. Port 3 – Load port output power

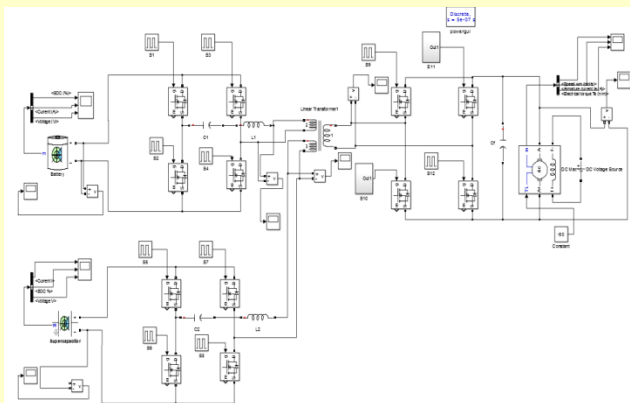


Fig. 22. Simulation circuit diagram with DC motor load for regenerative mode

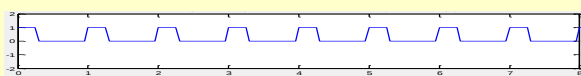


Fig. 17. Gating signal for switches S1, S9

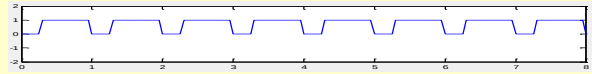


Fig. 18. Gating signal for switches S2, S10

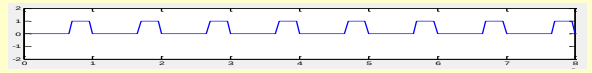


Fig. 19. Gating signal for switches S3, S11

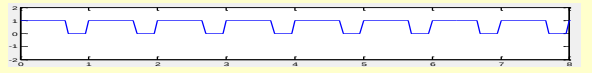


Fig. 19. Gating signal for switches S4, S12

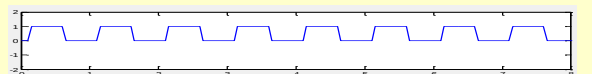


Fig. 21. Gating signal for switches S5, S8

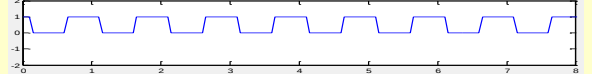


Fig. 22. Gating signal for switches S6, S7

represents voltage in volts and Y-axis represents time in  $10^{-4}$  seconds

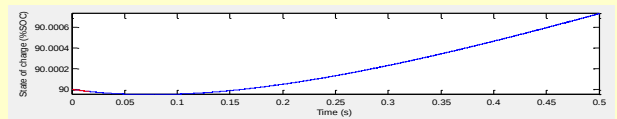


Fig. 23. Port 1- Battery state of charge

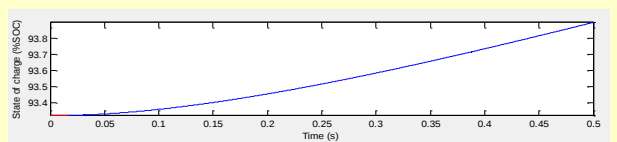


Fig.24. Port 2 – Supercapacitor state of charge

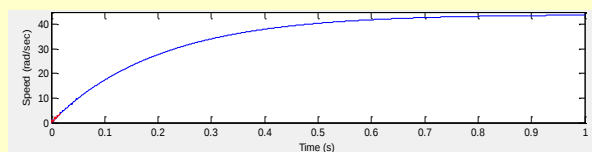


Fig. 25. DC motor speed

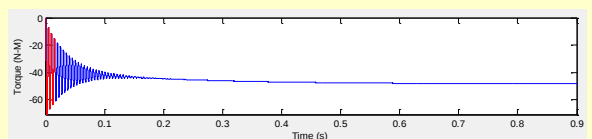


Fig. 26. DC motor torque

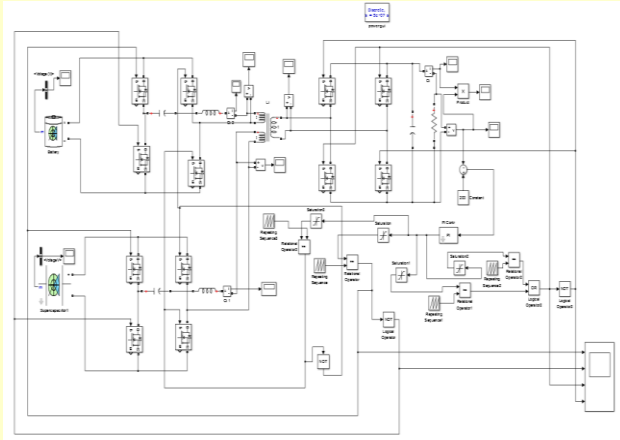


Fig. 37. Closed loop simulation diagram

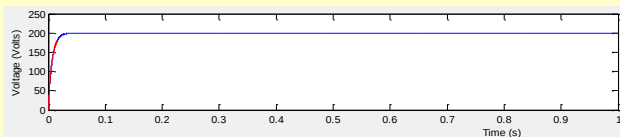


Fig. 38. Port 3 – Load port output voltage

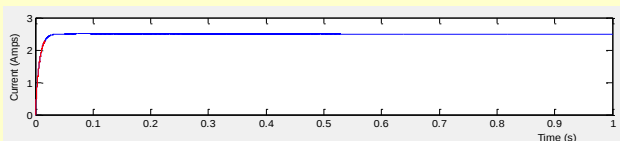


Fig. 39. Port 3 – Load port output current

### B. Closed loop simulation results

In Closed loop control technique the gating signals are controlled with the help of Proportional plus Integral (PI) controller . Such that despite of any changes in the input side parameters the output side parameters is made constant. With this control technique in closed loop simulation the output voltage obtained is 199.6 volt closer to the expected voltage of 200 Volts is obtained. Such that the drawbacks of conventional phase shift control technique is overcome.

## VI CONCLUSION

Asymmetrical PWM plus phase shift control of triple port isolated bidirectional dc-dc converter in which all the three ports are voltage fed ports is proposed in this paper to interface multiple energy storage systems such as battery and supercapacitor. It is shown that from the analysis and simulation results the power flow between the ports can be controlled by phase shifting the square wave outputs of the three active bridges and in addition to this duty cycle of the switches are varied such that voltage mismatch between the input and output side of ports is overcome and wider ZVS range is obtained.

## REFERENCES

- [1] Amari Mansour, Bacha Faouzi, Ghouili Jamel and Elgharbi Ismahen, "Design and analysis of high frequency dc-dc converters for fuel cell and super-capacitor used in electric vehicle," International Journal Of Hydrogen Energy, ELSEVIER, vol. 39, pp.1580-1592, May 2014.
- [2] B.S. Nathan and V.R. Ramanarayanan "Analaysis simulation and design of series resonant converter for high voltage applications", Proceedings of IEEE International Conference on Industrial Technology, vol. 1, no. 2, pp.688-693, December 2000.
- [3] Dehong Xu, Chuanhong Zhao and Haifeng Fan, "A PWM plus phase shift control bidirectional DC–DC converters", IEEE Trans. Power Electron., vol. 19, no.3, pp.666-675, 2004.
- [4] Dongzhi Wang, Weige Zhang and Jingxin Li, "A PWM plus phase shift control

strategy for Dual Active Bridge dc-dc converter in electric vehicle charging / discharging System”, ITEC Asia – Pacific, Beijing, pp.1-5, 2014.

- [5] Haimin Tao, A. Kotsopoulos, J.L. Duarte and M.A.M. Hendrix, “Triple half-bridge bi-directional converter controlled by phase shift and PWM,” in Proc. IEEE Appl. Power Electron. Conf. Expo (APEC), pp.1256- 1262, 2006.
- [6] Haimin Tao, J.L. Duarte and M.A.M. Hendrix, “Three port triple half bridge bidirectional converter with zero voltage switching,” IEEE Trans. Power Electron., vol. 23, no.2, pp.782-791, March 2008.
- [7] H. Krishnaswami and N. Mohan, “A current-fed three port bi-directional dc-dc converter,” in proc. IEEE Int. Telecommun. Energy conf. (INTELEC), pp.523-526, 2007.
- [8] H. Krishnaswami and N. Mohan , “Constant switching frequency series resonant three port bi-directional dc-dc converters”, in Proc. IEEE Power Electron. Spec. Conf. (PESC), pp.1640-1645, 2008.
- [9] H. Krishnaswami and N. Mohan, “Three port series-resonant dc-dc converter to interface renewable energy sources with bidirectional load and energy storage ports”, IEEE Trans. Power Electron., vol. 24, no.10, pp.2289-2297, October 2009.
- [10] K. Wang, C.Y. Lin, L. Zhu, D. Qu, F.C. Lee and J.S. Lai, “Bi-directional dc-dc converters for fuel cell systems,” IEEE Trans.Power Electron., vol. 13, pp. 47-51, 1998.
- [11] K. Sahay and B. Dwivedi, “Design and analysis of supercapacitors energy storage system for energy stabilization of distribution network,” Electrical Power Quality and Utilization, Journal, vol. 15, no.1, pp.25-32, 2009.
- [12] Lei Wang , Zhan Wang and Hui L, “Asymmetrical duty cycle control and decoupled power flow design of three-port bi-directional dc-dc converter for fuel cell vehicle application”, IEEE Trans. Power Electron, vol. 27, no.2, pp.891-904, 2012.