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Closed Loop Control of Triple Active Bridge for Electric Vehicles

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Abstract **The Battery-operated vehicles and hybrid vehicles are to replace conventional vehicles on the Indian roads as per the initiatives, guidelines and the time line set up by the government. The areas requiring development as per the literature are: the converter technology and energy storage systems. The bottleneck of the energy storage systems is being met by the usage of Li-ion batteries. The Bi-directional DC to DC converters are inevitable in Electrical and Hybrid Electrical Vehicles. In this paper, the DC to DC converters suitable for EV have been studied and the detailed study is made on Triple Active Bridge (TAB). The TAB is used as a single input dual output converter that a charges the battery and runs the motor as per the demand. It also recharges the battery subject to the SOC status of the battery through regenerative braking and discharges the battery to run the motor. Both open loop and closed loop operations of TAB are simulated using MATLAB SIMULINK with induction motor and PMSM as loads.**

Keywords — Dual Active Bridge, Triple Active Bridge, Electric Vehicles, State of Charge, Induction Motor.

INTRODUCTION

The use of battery-operated electric vehicles (EVs) and Hybrid Electric Vehicles (HEV) has been increased in recent years. While the battery-operated vehicles EVs operate with battery as the main source, the HEVs use both fuel and electricity for the propulsion of vehicle. In both the type of vehicles battery plays a vital role as sufficient amount of battery capacity is necessary to operate the vehicle effectively.

In battery-operated electric vehicles, battery power is needed to propel the motor, whereas in hybrid electric vehicles battery power is needed to accelerate the vehicle during dynamic loads such as initial acceleration and hill-climbing, etc. Hence it is necessary to maintain the state of charge (SOC) of the battery to improve its performance.

The battery can be charged through a DC charger or from an AC grid which uses a rectifier and an inverter. A small percentage of the motor power can be recovered and fed to the battery obtained as regenerative power from the traction motor.

as the battery is charged through regenerative power, the power flow in the battery is reversed therefore evs need bi-directional dc/dc converters for charging and discharging the battery.

thus a dc to dc converter is an important component of the hybrid electric vehicle (hev) system. the literature survey justifies the need for bi-directional dc/dc converters in evs with suitable drive train arrangement. there is a number of dc –dc converters being used. the various types of converters used are bidirectional single input single output (siso), single input dual output (sido), dual input single output (diso) or dual input dual output (dido). the interleaved siso and diso converters have exhibited performances better than the boost and the buck converters. however, the bidirectional converters have isolation problem [1]. this problem is addressed in the literature by using various topologies of dual active bridge dc – dc converter. the dual active bridge (dab) converters cannot be used for multi input and multi output operations from a single converter. the triple active bridge (tab) dc-dc converter is suitable for the above said operations [2]

dc-dc converter in evs enables to use lower capacity battery thus reducing the size and complexity of the circuit. during discharging mode, dc/dc converter boosts the voltage to a level that equals the motor terminal voltage, whereas during charging mode it bucks the voltage to a level that equals the battery voltage.

this paper contains a literature survey that includes the study of various bi-directional dc/dc converters and the detailed study and analysis of tab. the paper explains the application of tab in electric vehicles to maintain the State of Charge (SOC) of the battery. It also explains the circuit arrangement using TAB as an electrical medium to charge and discharge the battery. It also explains the various modes of operation of the circuit and simulation of the circuit in open loop and closed loop modes using matlab simulink.

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This paper is organised as follows: Section I explains the different modes of operation of the triple active bridge converter. Section II deals with the mathematical analysis of TAB, Section III explains with the power flow during various operating modes in the TAB. Section IV gives the simulation model and section V and VI of the paper gives the results and conclusion.

I. Triple active bridge converter(tab*)*

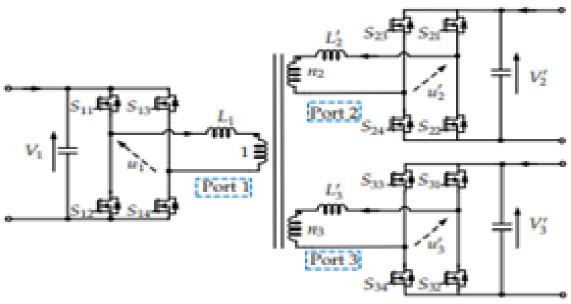

Figure:1 Power of circuit of Triple active bridge converter

The converter uses a high-frequency transformer that has a leakage inductance for power transfer. The power transmission is affected by the magnitudes of the voltages, phase shift angles, and leakage inductances of the high-frequency transformer [2]. The leakage inductances of the windings of the high-frequency transformer, acts as energy transfer elements [3].
The converter allows a flexible power transfer between three elements using various operating modes.

Operating modes of triple active bridge converter
By controlling the phase shift angles, the TAB converter can be operated in many modes, as shown in Figures below

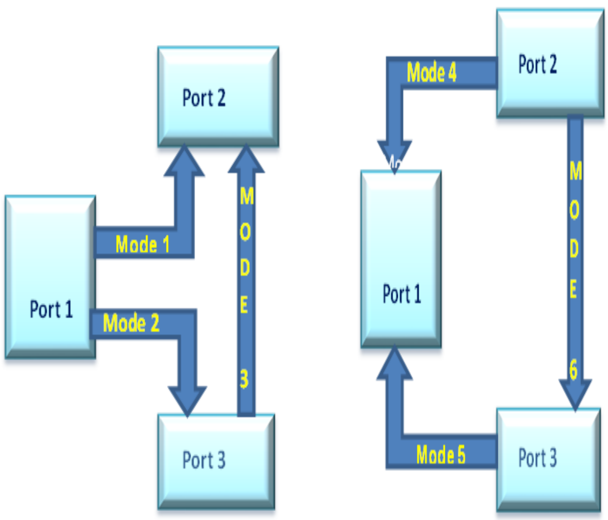

Figure: 2. Single input single output (SISO)

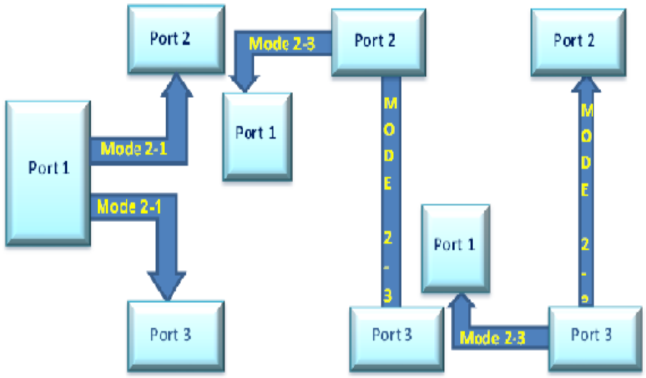

Figure: 3 Single input dual output (SIDO).

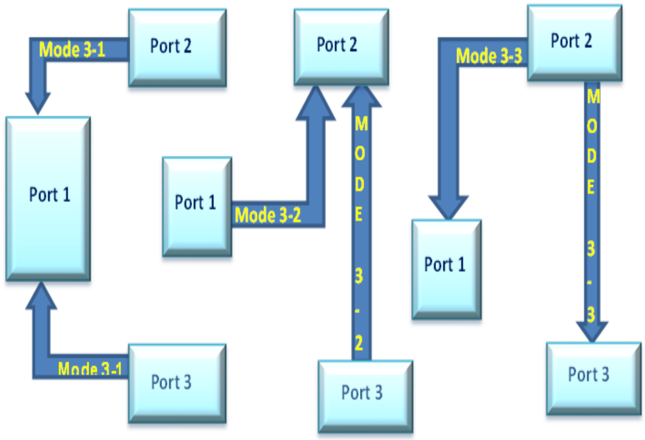

Figure: 4 Dual input single output (DISO)

It can be categorized into three groups. The single input single output (SISO) mode where electricity is transferred from one port to another while the third port is not powered. When power is supplied to two ports from a single port, the single input dual output (SIDO) mode is used. In dual input single output (DISO) mode, power from one port is supplied to the other two. [4], this demonstrates the TAB converter's adaptability in power transmission.

II A. EQUIVQLENT CIRCUIT OF TAB

To control and analyze this converter, it needs to be modeled as a delta connection [4] as is shown in Figure.

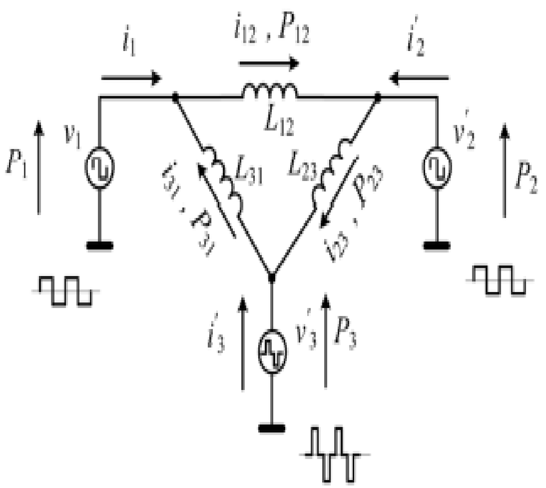

Figure: 5 Equivalent Circuit of Triple-Active-Bridge Converter

As is evident from the figure, each port is linked to the other two ports by an inductance. The amount of power delivered between each pair of ports is determined by the inductance and phase shift between them.

B. Power flow analysis of TAB

The phase shift of port 2 with respect to port 1 is taken as $ø_2$ and phase shift of port 3 with respect to port 1 is taken as $ø_3$.

Therefore the three-port power transfer equations [5] can be defined as,

$$P_1 = \frac{V_1\,V_2}{2\pi f s L_{12}} \emptyset_2\,(1 - |\emptyset_2|) + \frac{V_1\,V_3}{2\pi f s L_{13}} \emptyset_2\,(1 - |\emptyset_3|) \quad (1)$$

$$P_2 = \frac{V_1\,V_2}{2\pi f s L_{12}} \emptyset_2\,(1 - |\emptyset_2|) + \frac{V_2\,V_3}{2\pi f s L_{23}} (\emptyset_2 - \emptyset_3)(1 - |\emptyset_2 - \emptyset_3|)$$
(2)

$$P_3 = \frac{V_1\,V_2}{2\pi f s L_{12}} \emptyset_2\,(1 - |\emptyset_2|) + \frac{V_3\,V_1}{2\pi f s L_{23}} (\emptyset_3 - \emptyset_2)\,(1 - |\emptyset_3 - \emptyset_2|)$$
(3)

Where, L_1, L_2 and L_3 are the leakage inductances of each port of the network in its star equivalent circuit referred to port 1 [6].

C. Motors For Electric Vehicles

The power converter is used to supply the proper voltage and current to the electric motor. The electronic controller directs the power converter to control the operation of the electric motor to provide suitable torque and speed in response to the driver's command [7].

Unlike motors used in industrial applications, motors used in EVs and HEVs require frequent starts and stops, a large quantity of acceleration/deceleration, high torque and low-speed hill climbing, low torque and high-speed cruising, and a truly wide speed range of operation. The motors used in EVs and HEVs are divided into two types: commutator motors and commutator-less motors.

Commutator motors are mostly ordinary direct current (DC) motors such as series-excited, shunt-excited, compound-excited, and independently excited.The arcing produced by the armature coils on the brush commutator surface, which generates heat, wear, and electromagnetic interference (EMI), is one of the downsides of brushed DC motors [8]. These properties of the brushed motor imply that it is better suited for applications where great efficiency is not a major issue. This makes the usage of this type of motor in EV applications less appealing.

Commutator-less electric motors such Induction motor, Switched reluctance motor, Brushless motors have just entered a new era due to technological advancements. Increased efficiency, higher power density, and lower operating costs are some of the benefits. They are also more reliable and maintenance-free than commutator DC motors, making commutator-less electric motors more desirable.

D. Batteries for electric vehicles

The power converter is responsible for transferring energy from the battery to the engine, as well as supplying electricity from the generator to the battery. With the help of the transmission system, the engine's mechanical power is transferred to the wheels [9]. Lead-acid, nickel-metal hydride and lithium-ion batteries are the mostly used batteries for EV and HEV applications [10].

The state of charge is an important battery parameter (SOC). The ratio of residual capacity to completely charged capacity is known as SOC [12]. According to this definition, a completely charged battery has a SOC of 100%, while a fully depleted battery has a SOC of 0%.

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III A. OPERATION OF TRIPLE ACTIVE BRIDGE FOR ELECTRIC VEHICLES

The TAB acts as a channel for power transfer to various devices connected to its ports. The three-phase ac power grid is connected to Port 1 as an input, the battery is connected to Port 2, and an electric motor is connected to Port 3 of the TAB as shown in the figure. Out of the three operating modes of TAB described above, this paper describes the single input single output mode of operation.

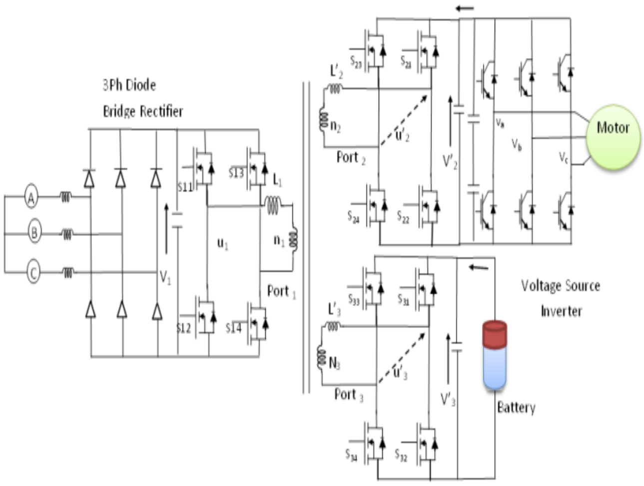

Figure: 5 Circuit diagram Battery and Motor as outputs and grid as input

The circuit operates mainly in three modes,

B. Battery charging mode

The battery is initially charged through a three-phase AC grid connected to port1. The three phase diode bridge rectifier converts available ac voltage to dc voltage. This dc voltage is then fed into a single phase full bridge converter, which generates a square wave output. The single phase full bridge converter connected to port$_2$ functions as a rectifier, the output of which can be stored in a battery.

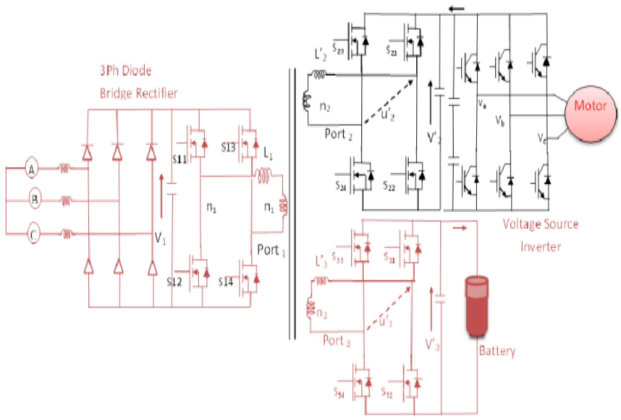

Figure: 6 Conduction diagram during battery charging mode

During this mode, the energy is transferred to battery connected to port3 from AC grid connected to port1 whereas the motor connected to port2 is completely isolated.

C. Battery Discharging mode

Furthermore, the battery's stored energy is discharged to the electric motor for propulsion or to drive the load. The single phase converter connected to port 2 functions as an inverter and outputs a square wave.
The single phase converter attached to port 3 serves as a rectifier, the output of which is sent into the voltage source inverter.
The voltage source inverter serves as a motor drive.

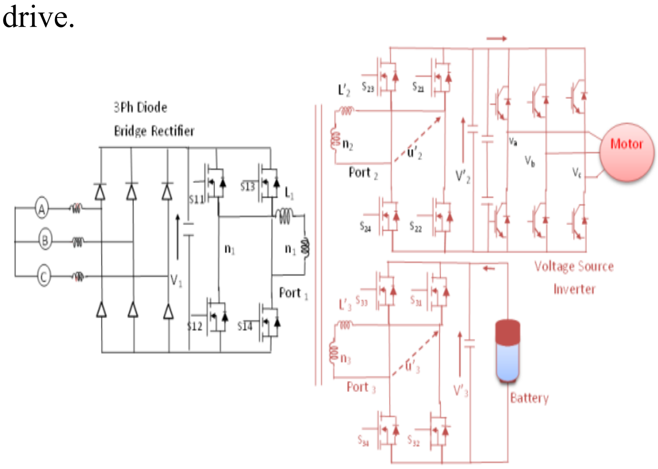

Figure: 7 Conduction diagram during battery discharging mode

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During this mode, the energy stored in the battery is transferred to motor connected to port2 whereas the AC grid connected to port1 is completely isolated.

D. Regenerative braking mode

The voltage source inverter can drive the motor in the method shown above. As a result, by supplying negative torque to the motor, the kinetic energy of the motor can be turned into electrical energy. When a negative torque is supplied to the motor, it rotates in the opposite direction and serves as a generator. Only the body diodes of the switches activate when the driving pulses to the voltage source inverter are removed. This voltage source inverter is now capable of functioning as a diode bridge rectifier

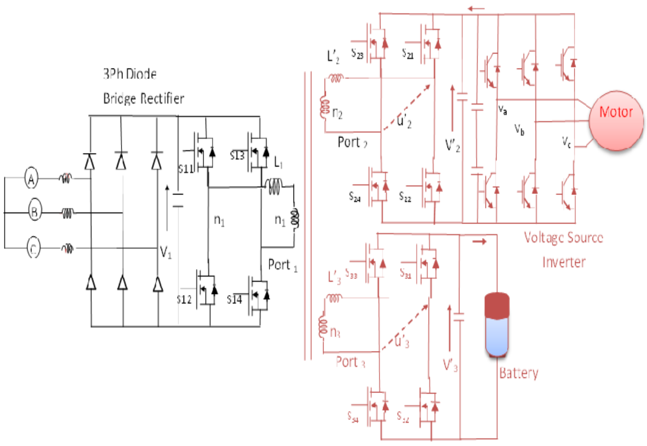

Figure: 8 Conduction diagram during regenerative braking mode

E. Technical specifications

a. AC grid

Input voltage to AC Grid (V_{LRMS}) = 415V
Frequency = 50Hz
Phase angle of phase A= 0˚

b. Diode bridge rectifier

Snubber Resistance = 10^5 Ω
No. Of Arms = 3
Snubber capacitor = 10^{-6} F

c. Transformer

Power = 10KVA
Frequency = 15 KHz
Winding 1 parameters = 600V_{Rms} 0.05Ω 10^{-6}H
Winding 2 parameters = 400V_{Rms} 0.05Ω 10^{-6}H
Winding 3 parameters = 300V_{Rms} 0.05Ω 10^{-6}H

d. Battery

Nominal Voltage = 250V
Rated capacity = 200Ah
Initial state of charge =10%

e. Motor

Torque = 24 N
Voltage = 300V
Speed = 2300RPM

IV SIMULATION MODEL

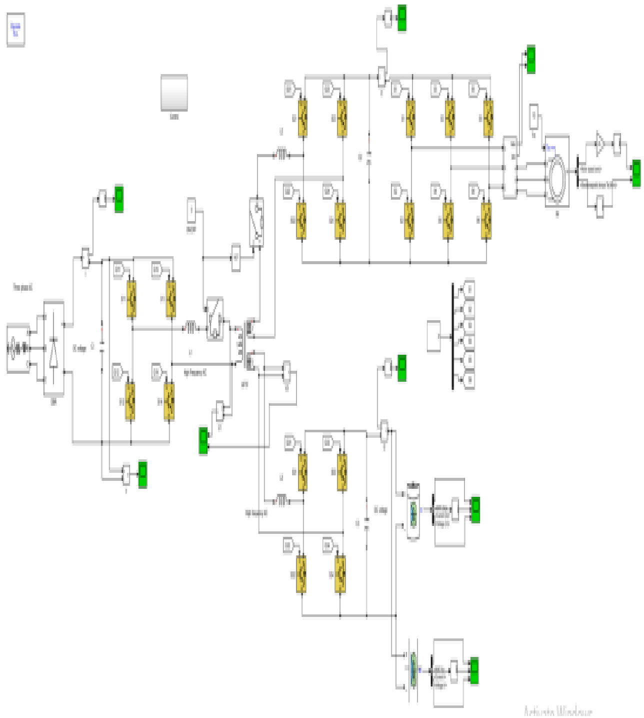

Figure: 9a Proposed model with TAB connected to grid, battery, voltage source inverter and motor

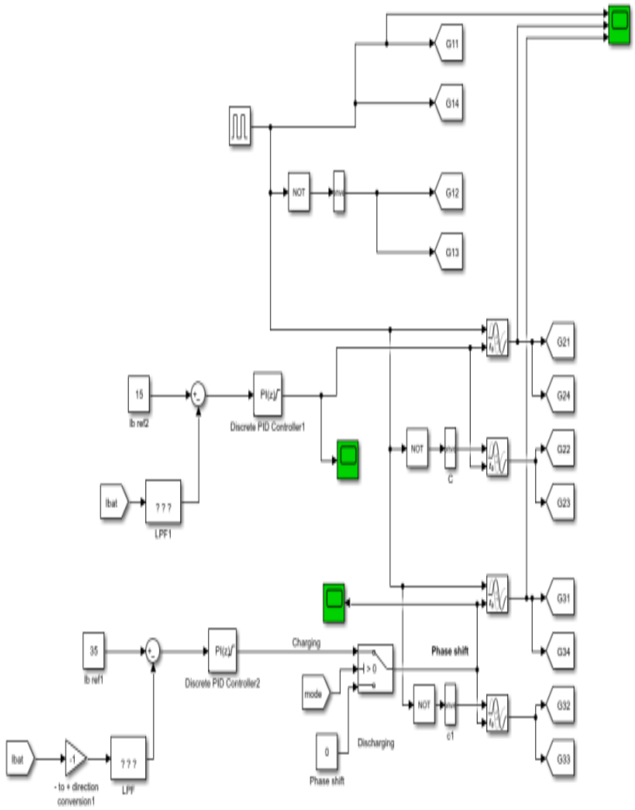

Figure: 9b Closed loop control with PI Controller for the TAB circuit

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V RESULTS

a. During charging

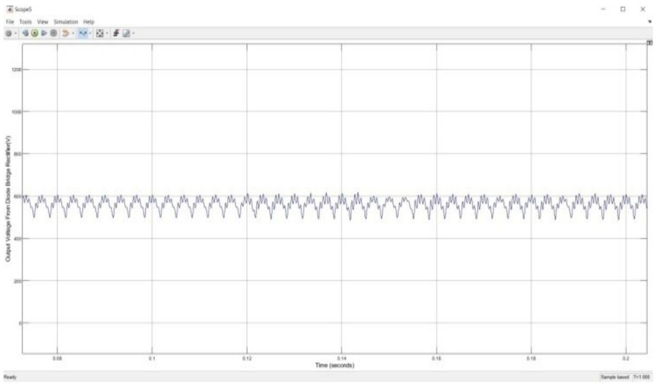

Figure: 10 Rectified output voltage during charging

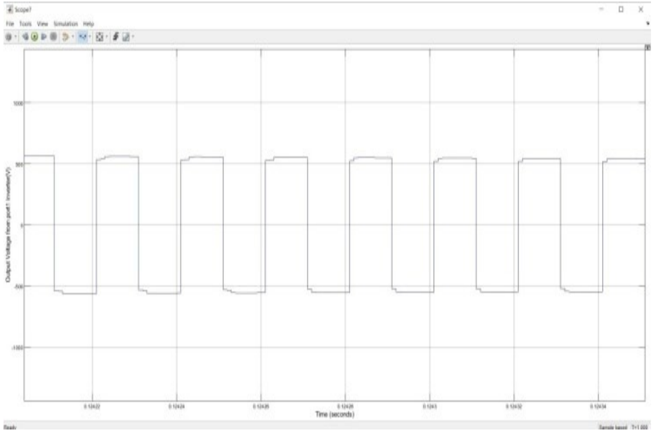

Figure: 11 $Port_1$ output voltage

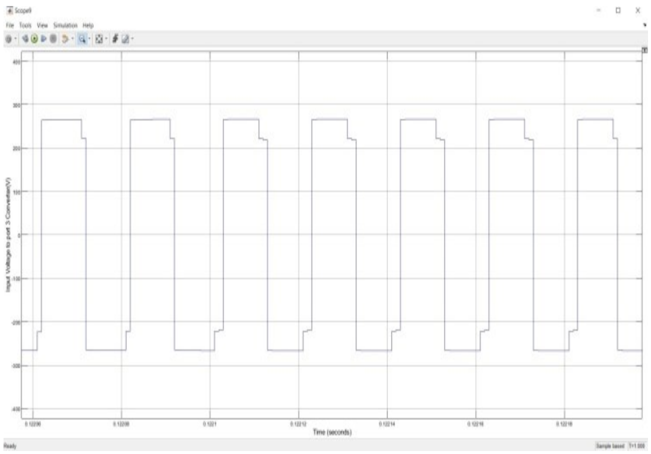

Figure: 12 $Port_3$ input voltage

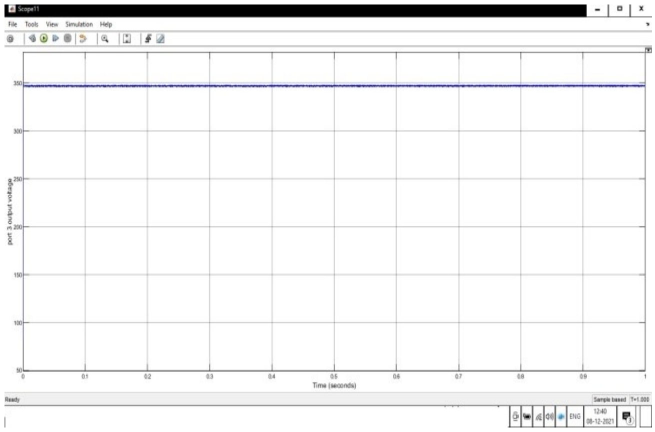

Figure: 13 $Port_3$ output voltage

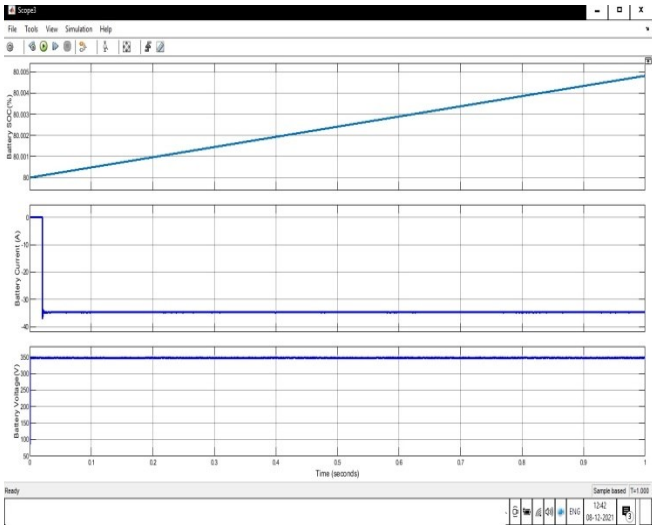

Figure: 14 Battery characteristics

b. During discharging

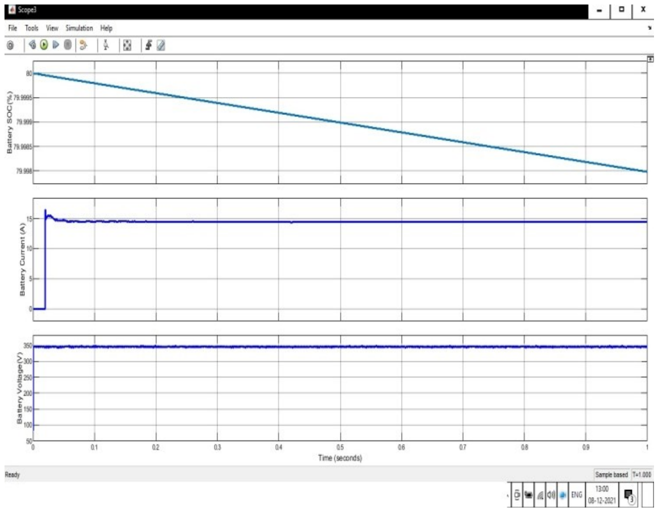

Figure: 15 Battery characteristics

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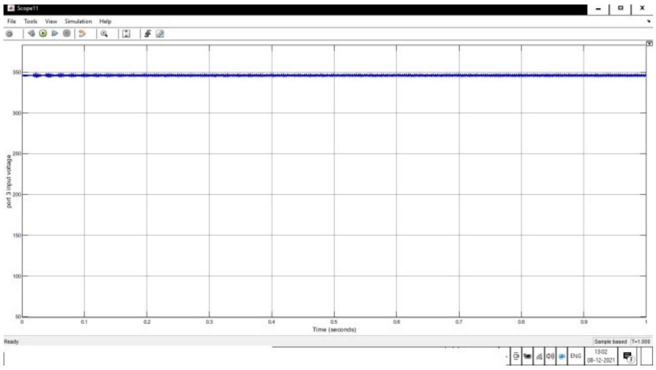

Figure: 16 Port$_3$ input voltage

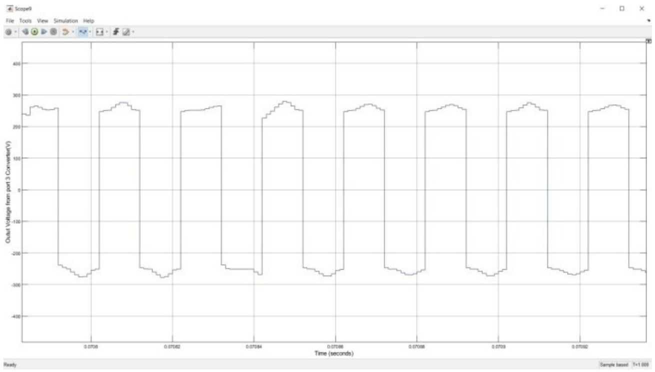

Figure: 17 Port$_3$ output voltages

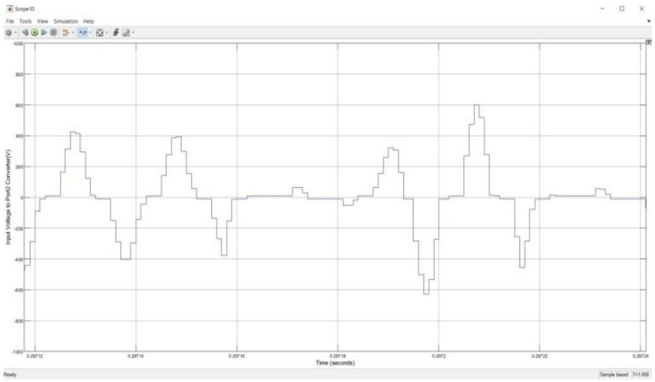

Figure: 18 Port$_2$ input voltage

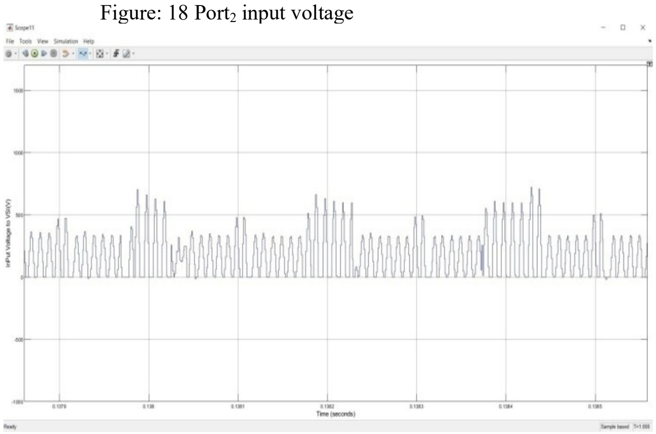

Figure: 19 Input voltages to VSI

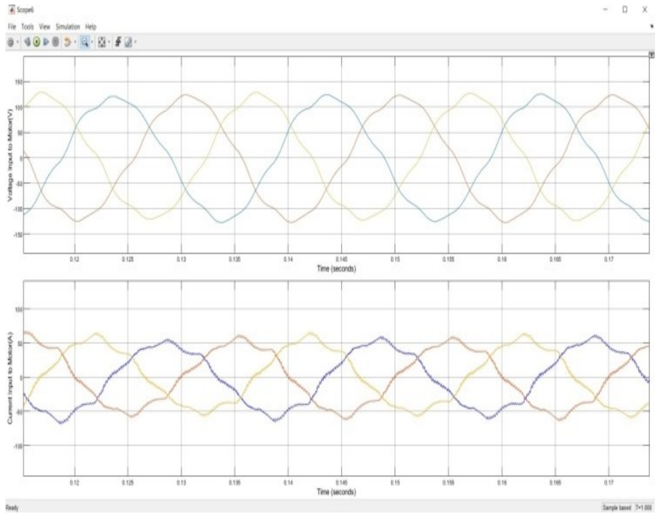

Figure: 20 Input voltage and current to IM

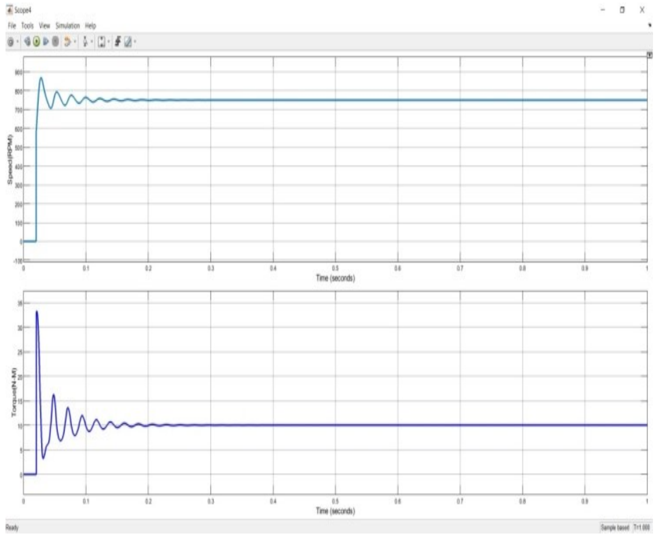

Figure: 21 Speed and torque of IM

c. During regenerative braking

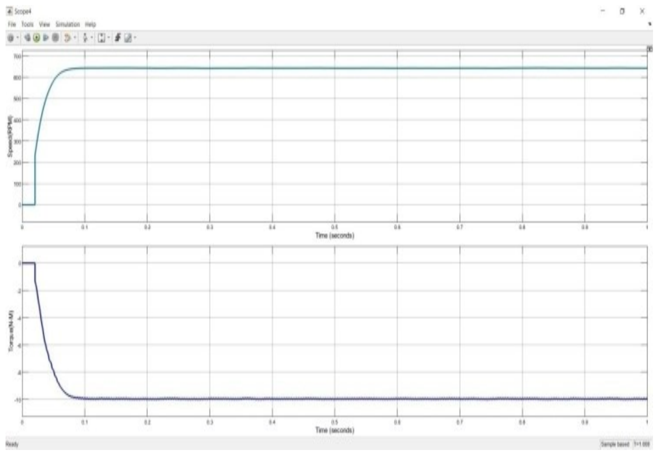

Figure: 22 Speed and torque of motor

International Journal of Engineering Research & Technology (IJERT)
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Volume 13, Issue 01 January 2024

VI CONCLUSION

In this paper TAB is used to transfer the power between three ports which contains AC grid connected to port 1, Electric Motor connected to port 2 and battery connected to port 3. The battery is charged from ac grid via port 1 and port 3 while port 2 is isolated and the battery is discharged to the electric motor via port 2 and port 3 while port 1 is isolated. All the modes of operation are shown for induction machine. Each bridge is controlled by phase shift PWM technique which decides the flow of power in each port. It is observed that TAB facilitates power transfer at different voltage levels.
The phase delay angle is controlled by feedback loop control with PI controller as phase shift controller with input taken from the comparison of reference current and measured currents of the battery.
Application of TAB for electric vehicles has been implemented. TAB can also be used for other applications such as DC micro grids, electric aircrafts and in uninterrupted power supplies data centers etc.

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