Simplified Power Converter for Integrated Traction Energy Storage

S. NISCHALA[1], G. BHARGAVI[2]

[1]Assistant Professor, Dept of EEE, Sri Indu Institute of Engineering & Technology, Hyderabad, TS, India,

[2]Assistant Professor, Dept of EEE, Sri Indu Institute of Engineering & Technology, Hyderabad, TS, India,

Abstract: Electrical energy storage has a significant role to play in improving the performance of future electric traction systems. This paper proposes a new power electronics topology that integrates the energy storage power electronics with those of the inverter drive system. This topology reduces weight and component count compared with previous topologies but still allows the use of standard machines. Practical results from a laboratory test system are shown, and indicative energy savings for a full-sized system are presented. A study on a City Class Tram on the public transportation system in Blackpool, U.K., shows that clear energy savings may be made by employing ultra capacitor energy storage with the proposed topology. The new power electronic converter proposed in this paper combines two parallel inverters. The two parallel inverters work from two separate dc sources:

- the traction supply source
- the energy storage source.

The first inverter is connected to the traction supply source. The second inverter is connected to the ESS. Bidirectional switches are employed to connect the ESS to the motor windings; this is required to prevent current flowing from the traction supply system to the ESS when the inverters are connected in parallel.

Keywords: Energy Conversion, Energy Storage, Power Control, Traction Power Supplies.

I. INTRODUCTION

With growing importance being placed on decarbonising the world economy and achieving energy security, electrified public transportation is playing a progressively greater role in society. Compared with personal transportation, a substantial energy saving is achieved with public transportation, particularly at peak commuter times. Further carbon savings may be made since the electrical network would allow renewable and low-carbon energy to provide motive power. The energy consumed in an electrified transit system can further be reduced by installing energy storage systems (ESSs) on board vehicles. Energy storage devices can be used to regenerate energy during braking, energy which would otherwise be dissipated in either mechanical brakes or braking resistors. This energy can then be reused. A traction control system (TCS), also known as anti-slip regulation (ASR), is typically (but not necessarily) a secondary function of the anti-lock braking system (ABS) on production motor vehicles, designed to prevent loss of traction of driven road wheels. When invoked it therefore enhances driver control as throttle input applied is mis-matched to road surface conditions (due to varying factors) being unable to manage applied torque. Intervention consists of one or more of the following:

- Reduces or suppress spark sequence to one or more cylinders
- Reduce fuel supply to one or more cylinders
- Brake force applied at one or more wheels
- Close the throttle, if the vehicle is fitted with drive by wire throttle
- In turbo-charged vehicles, a boost control solenoid can be actuated to reduce boost and therefore engine power.

Typically, traction control systems share the electro-hydraulic brake actuator (but does not use the conventional master cylinder and servo), and wheel speed sensors with the anti-lock braking system. The basic idea behind the need of a traction control system is the difference between traction of different wheels evidencing apparent loss of road grip that compromise steering control and stability of vehicles. Difference in slip may occur due to turning of a vehicle or differently varying road conditions for different wheels. At high speeds, when a car tends to turn, its outer and inner wheels are subjected to different speed of rotation, that is conventionally controlled by using a differential. A further enhancement of the differential is to employ an active differential that can vary the amount of power being delivered to outer and inner wheels according to the need (for example, if, while turning right, outward slip (equivalently saying, 'yaw') is sensed, active differential may deliver more power to the outer wheel, so as to minimize the yaw (that is basically the degree to which the front and rear wheels of a car are out of line.) Active-differential, in turn, is controlled by an assembly of electromechanical sensors collaborating with a traction control unit. When the traction control computer (often incorporated into another control unit, like the anti-lock braking system module) detects one or more driven wheels spinning significantly faster than another, it invokes the ABS electronic control unit to apply brake friction to wheels spinning with lessened traction. Braking action on slipping wheel(s) will cause power transfer to wheel axle(s) with traction due to the mechanical action within a differential. All-wheel drive AWD vehicles often have an electronically controlled coupling system in the transfer case or transaxle engaged (active part-time AWD), or locked-up tighter (in a true full-time set up driving all wheels with some power all the time) to supply non-slipping wheels with (more) torque. This often occurs in conjunction with the power train computer reducing available engine torque by electronically limiting throttle application and/or fuel delivery, retarding ignition spark, completely shutting down engine cylinders, and a number of other methods, depending on the vehicle and how much technology is used to control the engine and transmission.

II. ENERGY STORAGE VIABILITY

Such techniques have a long history. The Central London Railway was built with stations that were raised, meaning that trains had to climb a gradient to enter a station and descend when leaving a station [1]. This form of energy storage reduced losses a little; modern technology can today be far more effective. A study of the implementation of trackside energy storage on a U.S. West Coast Light Rail system showed potential energy savings of 23%. Financial considerations emphasize the benefits of reducing the peak energy demand [2], although this is dependent on energy tariffs. However, research on both locomotives [3] and plug-in-hybrid vehicles [4] has shown tha systems approach must be taken maximizing the utility of the storage and minimizing the extra weight added. The maximum energy available during braking depends on the kinetic energy and hence the speed and loading of the tram(see Fig. 1). The actual energy that may be captured is a more complex function, depending on the power and energy rating of the storage system, as well as the time function driving cycle of the tram over its normal route and the braking rate, due to the balance of energy recovered and the energy used to overcome mechanical losses. For this study, the braking power profile of the vehicle over a typical tram run on the Blackpool public transportation system was used since real (measured) drive cycle data were taken as part of this research project [5]. The effect on the drive cycle was determined by simulation using a model that incorporated the electrical system, the mechanical effects, and the drive cycle of the tram [5]. This model has been validated against site tests (see Fig. 2) for normal operation without energy storage for a City class tram (used for normal commercial passenger service; see Fig. 3) and a Centenary class tram (a low-cost high efficiency concept vehicle under development).

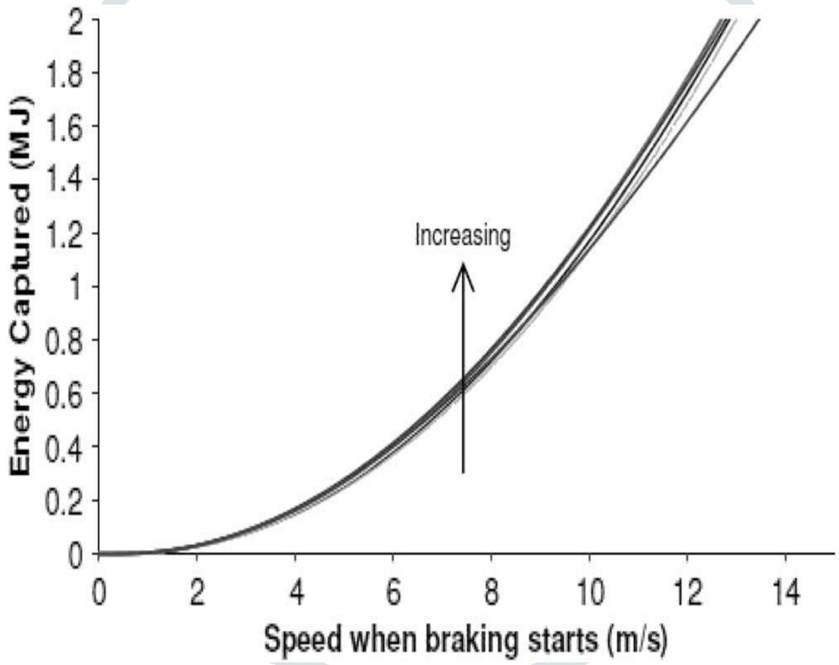

Fig.1. Braking energy available for a Blackpool city tram carrying 100 passengers, with different starting and braking speeds (braking speeds of 0.2–1.4 m/s2 in 0.2-m/s2 steps).

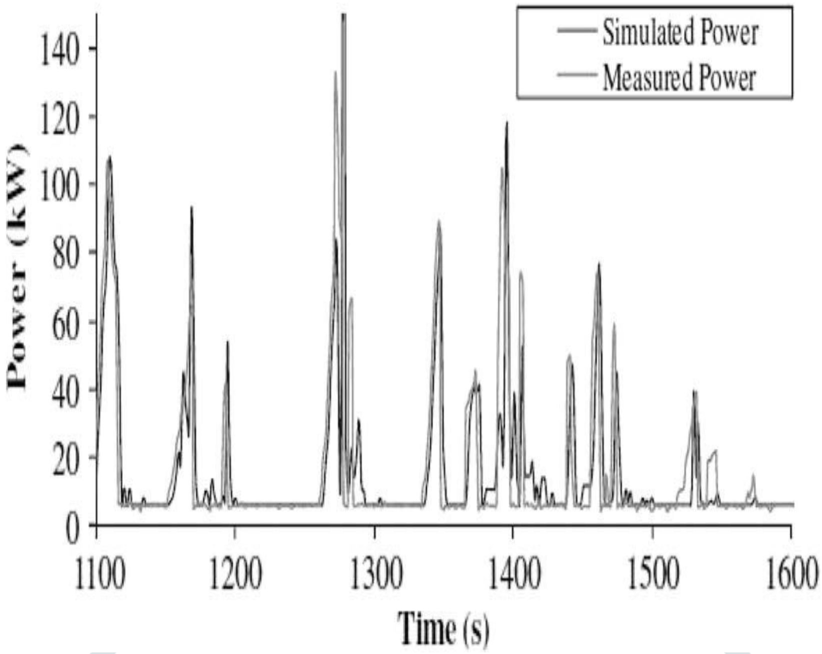

Fig.2. Simulation model validation against test data on Blackpool Centenary Class tram (without energy storage).

Fig.3. Tram power's city class tram.

By applying a saturation function to the braking power profile, limiting the power to the rating of the converter, and then integrating the braking power over the drive cycle, the energy captured using the specified converter rating can be found (see Fig. 4). It should be noted that due to the Blackpool tramway layout, much of the trams' operation is made up of short motor/coast/brake cycles. Selecting a point on the curve where it starts to flatten off allows a converter to be chosen, which captures a sufficient amount of the energy available. Two options are selected for consideration. The first is a 50-kW converter, potentially allowing 3.1 MJ of braking energy to be captured over the cycle. This solution minimizes the size of the converter while ensuring that a significant proportion of the available braking energy is captured. A second option of 100 kW, allowing a greater proportion of the energy to be captured, is also considered.

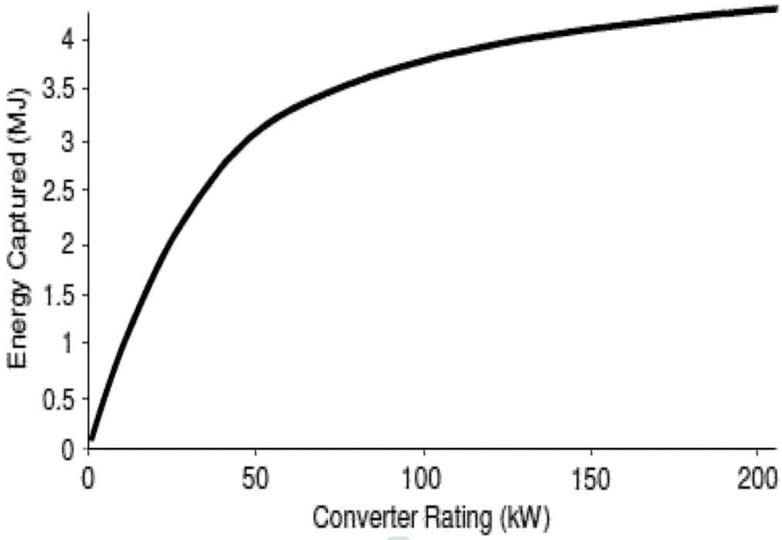

Fig.4. Braking energy captured for a Blackpool drive cycle city tram over a short drive cycle.

TABLE I: Energy Consumption Of Vehicle Components

	Electrical Energy dissipated (kWh/km) TARE (unloaded, 22,500kg)	*Electrical Energy dissipated (kWh/km), 100 passengers (29,700kg)*
Frictional Forces	0.172	0.172
Motor	0.254	0.395
Traction Inverter	0.191	0.277
Auxiliary	0.133	0.133
Braking	0.501	0.653
TOTAL	1.250	1.630

A. Choice of Energy Storage

For traction systems, robustness is paramount: an energy storage device in a traction application will be discharged every time a vehicle sets off and stops, and since this can equate to hundreds of times a day, it is essential that the degradation of an energy storage device due to the charge–discharge cycle is minimal. Maintenance requirements should be kept as low as possible. Additionally, a high power density is required, energy density is important but is less critical. Ultra capacitor energy storage devices meet these requirements. They also have no moving parts, further increasing reliability and robustness in mobile applications. In the subsequent discussion, ultra capacitors will be used as the energy storage device, and hence, the electrical converter must be capable of interfacing the ultra capacitor (dc) source to the remaining system. For the discussion of design decisions, data from an in-service City class tram on the Black pool tramway will be used.

III. ENERGY MANAGEMENT

During braking, as much of the braking energy as possible should be stored in the ultra capacitor. The braking energy not stored by the energy storage device is dissipated in braking resistors. However, the storage power is limited by the converter power, and the energy storage device must not be allowed to exceed its maximum voltage level. The converter systems are typically operated with a specific input voltage range for several reasons: to maintain operability, the ultra capacitor should not be allowed to fall below a minimum voltage level; little extra energy is available at low voltages since three quarters of the energy is available from the top half of the voltage range; and to extract power at the same rate requires more current at lower voltages. Therefore, when the ultra capacitor voltage falls below the minimum voltage, tractive power is supplied fully from the traction power supply. Analysis of the 22-ton City Class tram over the drive cycle gives the consumption levels in Table I, i.e., 1.25 kWh/kmunloaded (TARE value). The analysis shows that 40% of the energy used by the vehicle is dissipated in braking. This energy could potentially be used to charge an energy storage device. The energy storage device will also have losses, and hence, the calculated braking energy does not represent the potential energy saving. The Maxwell HTM Power Super capacitor [6] with a capacitance of 17 F was incorporated into the vehicle model [5] with a 50-kW converter. The ESS is added to both motor drive systems. The dc–dc converter model is implemented using an efficiency lookup table. The simulation results for the same cycle are shown in Table II. The simulation results show that for a vehicle with no passengers, a total of 0.997 kWh/km is consumed on a vehicle with energy storage with a 50-kW dc–dc converter over the drive cycle. This corresponds to a 0.253-kWh/km reduction in energy consumption, i.e., a 20% saving in energy over the drive cycle. The energy consumption is reduced by a further 0.058 kWh/km by using a 100-kW converter, increasing the energy saving to 25%. For a vehicle with 100 passengers, the energy saving is 0.293 kWh/km for a 50-kW converter (an 18%saving). For a 100-kW converter, the saving is increased by0.068 kWh/km (a 22% energy saving). The energy saving from the installation of a dc–dc converter ESS varies between 20%and 25%, depending on the loading conditions and the dc–dc converter rating.

TABLE II: Energy Dissipation With Energy Storage

	Electrical Energy dissipated (kWh/km)			
Converter	50kW DC-DC Converter		100kW DC-DC Converter	
Passenger loading	TARE	100 passengers	TARE	100 passengers
Frictional Forces	0.172	0.172	0.172	0.172
Motor	0.257	0.399	0.257	0.399
Traction Inverter	0.193	0.280	0.193	0.280
Auxiliary	0.133	0.133	0.133	0.133
ESS converter losses	0.061	0.071	0.076	0.092
ESS Losses	0.029	0.036	0.048	0.069
Braking Resistors	0.151	0.247	0.060	0.125
TOTAL	0.997	1.337	0.939	1.269

IV. CONVERTER SELECTION—PRIOR ART

While both track-side and onboard solutions are possible, having energy storage units on the tram has the advantage of putting the solution next to the problem. When multiple tramsrun on the same section of the network, the local energy storage capability is increased if each tram carries its own storage system (see Fig. 5).Installing energy storage devices onboard vehicles is not anew idea. The development of the Yver don Gyrobus began in1945 [7]. The bus was powered by a flywheel that drove an induction generator. The flywheel charged at three-phase charge points periodically. The Gyrobus required a complex propulsion system, consisting of three motors connected together through reduction gears. Each motor could be driven in two different pole configurations, effectively giving six different motor speed–gear configurations, covering the required speed range. Such a mechanically complex system is undesirable and perhaps resulted in the limited adaptation of the Gyrobus. Complex mechanical systems can now be replaced with modern power electronic drives, allowing a single induction motor to propel a vehicle across the entire speed range; see for example, Fig. 6.Minimizing the required rating of the dc–dc converter esessential to minimize the size, weight, and cost of the energy have to be sized for peak power level. The “standard solution” (Fig. 5) would use high-power dc–dc converters. These are xpensive and bulky [8], as they typically require large inductive energy storage components. A more compact alternative would be desirable. Some of the leading rolling stock manufacturers are developing tram products with energy storage devices. Alstom is testing a tram with onboard flywheel energy storage in Rotterdam [10]. Bombardier had developed the Mitrac Energy Saver, which has shown a 30% energy consumption reduction in Mannheim [11], [12]. The Nice tramway has a fleet of 20 Citadis trams that have NiMH batteries, allowing overhead line free operation for a section of the system [13]. Recent publications suggesting the implementation of an onboard energy storage use an arrangement based on that shown in Fig. 6. Steiner, together with other authors, has published a number of papers on the Bombardier Mitrac system, which is a successful example of the implementation of ultra capacitor energy storage in light rail systems, which is based on this configuration using a bidirectional insulated-gate bipolar transistor IGBT) chopper [14]–[16]. Other authors have also proposed and analyzed systems based on this configuration [17].

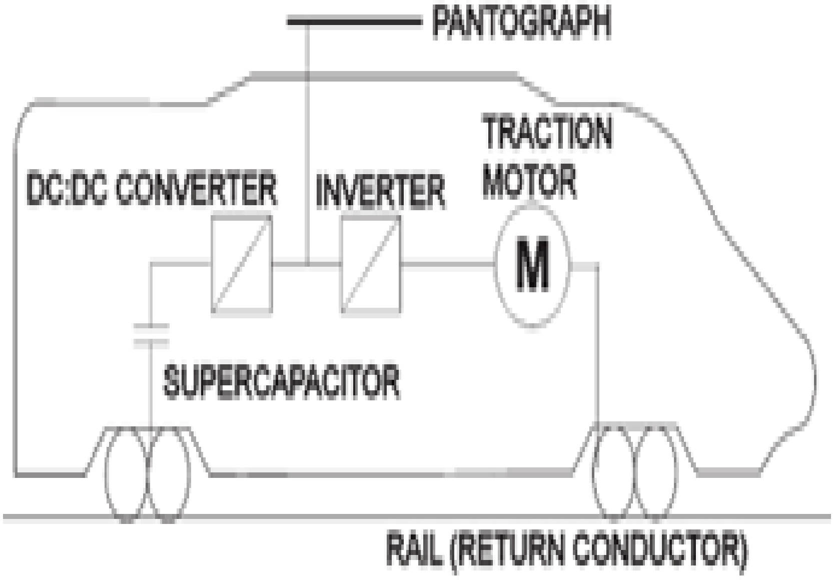

Fig.5. most common connection method of energy storage in electric traction.

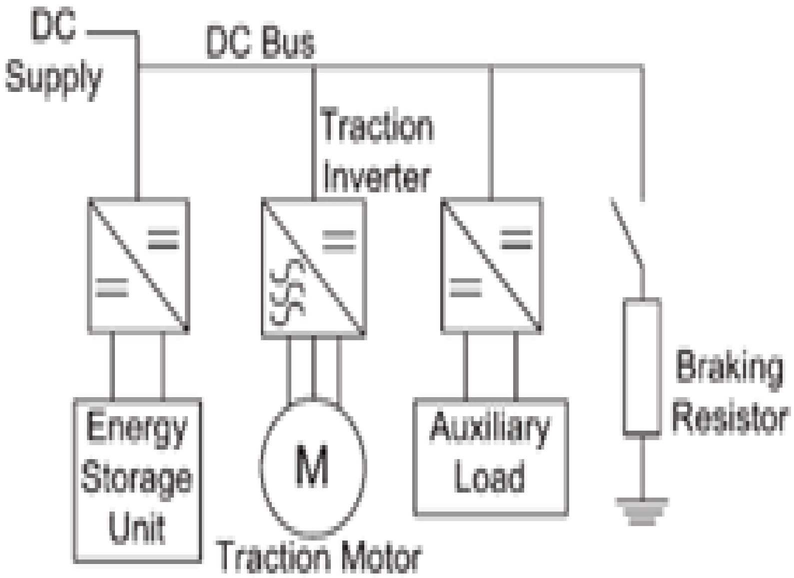

Fig.6. Typical constituents of light rail electrical system.

The energy storage converter employed in such systems is required to boost the energy storage unit voltage, ultimately meaning the converter requires bulky passive components. A solution has been proposed to overcome this issue, installing the ultra capacitors in series with the dc supply (see Fig. 7). Simulation results of this concept are promising, although practical tests performed to date have been unable to prove the concept [18]. A weakness of the standard configuration is that the energy flowing to and from the energy storage devices passes through two power electronic converters: 1) the traction inverter and 2) the energy storage converter. Connecting an energy storage inverter to the motor through an auxiliary transformer removes the requirement for the extra stage (see Fig. 8). This configuration requires additional transformers, which introduce additional mass and additional system losses, although these are smaller than that of a dc–dc converter. Laboratory tests have shown promising results [19], [20]. A cascaded two-level converter has been proposed as an alternative to four-level converter topologies [21] using one dc link. This circuit can be adapted, using two separate dc sources, at different voltage levels for traction applications [22]. Fig. 9 shows the layout of the proposed dual inverter-fed traction drive. A significant disadvantage of the design is the requirement to access both ends of the motor windings. This would require some traction motors to be modified.

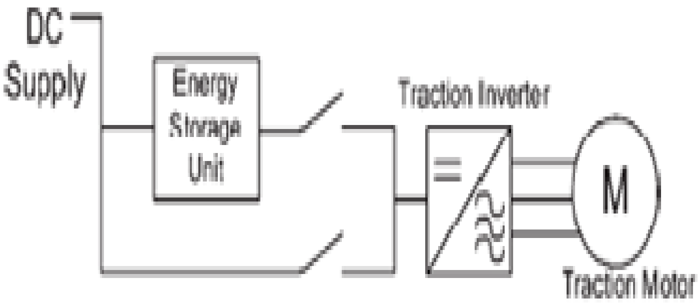

Fig.7. Energy storage connected in series with the dc supply.

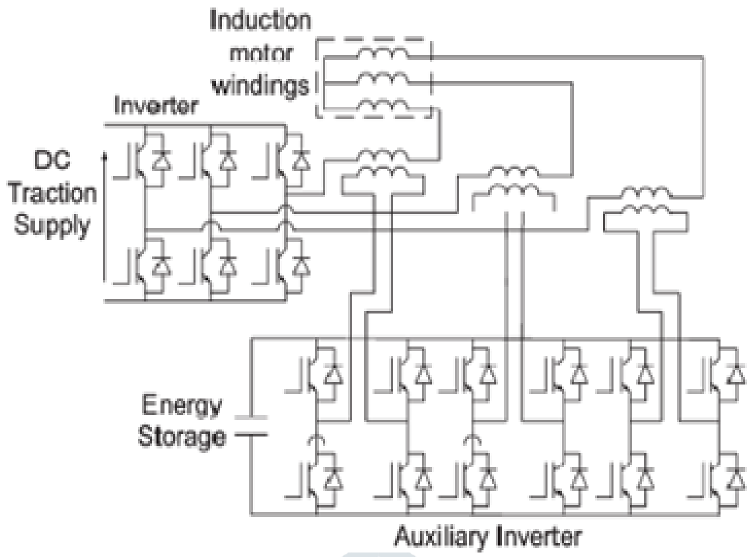

Fig.8. Configuration using transformer coils to inject current to the induction motor.

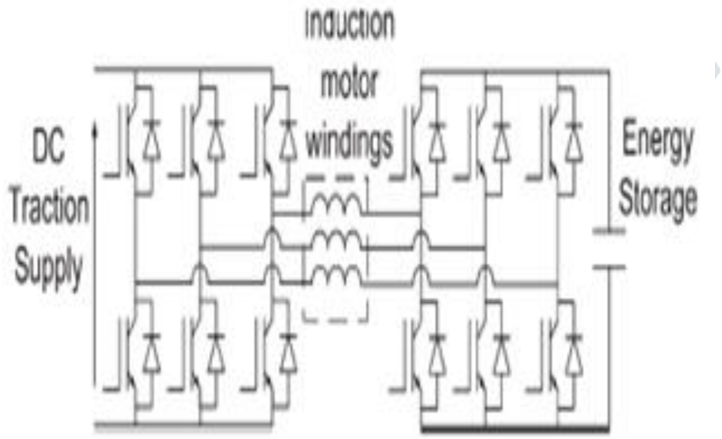

Fig.9. Dual inverter-fed traction drive.

V. NEW CONVERTER

The new power electronic converter proposed in this paper combines two parallel inverters. The two parallel inverters work from two separate dc sources: 1) the traction supply source and 2) the energy storage source. The first inverter is connected to the traction supply source. The second inverter is connected to the ESS. Bidirectional switches are employed to connect the ESS to the motor windings; this is required to prevent current flowing from the traction supply system to the ESS when the inverters are connected in parallel. Two IGBTs and anti parallel diodes are connected together to create a bidirectional switch. Fig. 10 shows the two inverters connected together. Both sets of inverters have switches connecting the motors to ground (IGBTs 2, 4, and 6 and IGBTs 13, 14, and 15). As they are in parallel, they can be replaced with a single set of switches, and therefore, IGBTs 13, 14, and 15 (shown by dashed lines) can be removed (see Fig. 11).

A. Operation

By switching between the two separate inverters, the power electronic converter can be used to interleave the two sources. The circuit clearly works best if the energy storage unit is designed to have a nominal dc voltage comparable with that of the normal dc traction supply. The three modes of operation, i.e., traction supply inverter, energy storage inverter, and interleaved operation, are subsequently described. Standard Inverter Operation: The bidirectional switches are off (IGBT pairs: 7 and 8, 9 and 10, and 11 and 12), and a pulse width- modulation (PWM) signal is generated to control IGBTs 1, 2, 3, 4, 5, and 6. In this mode of operation, the circuit behaves as a conventional inverter. Energy Storage Source Inverter Operation: IGBTs 7, 9, and 11 are turned on, and IGBTs 1, 3, and 5 are turned off. IGBTs 8, 10, and 12 and IGBTs 2, 4, and 6 are driven using a PWM signal, and the circuit behaves like an inverter with the energy storage device as the energy source. This mode also allows the induction motor to operate in a regenerative braking region of operation, braking the vehicle, and charging the energy storage device.

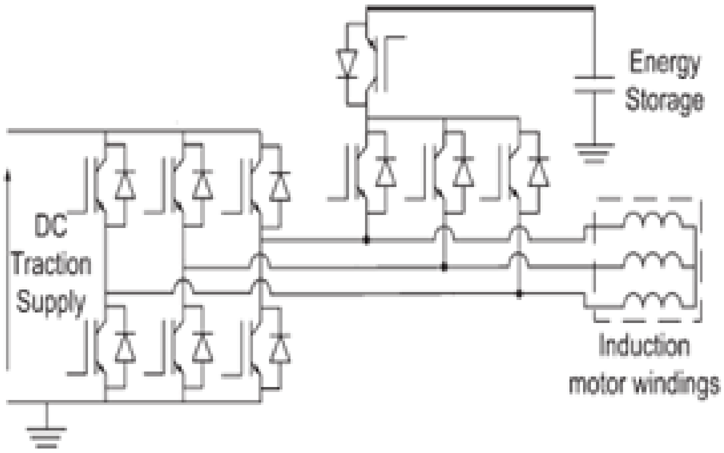

Fig.10. Novel converter arrangement-Type 2.

Dual-Source Inverter Operation: By switching between the standard inverter mode and the energy storage source inverter mode, the circuit can be used to drive the induction motor from either source. By rapidly switching between the two modes of operation, the novel power electronic converter can be used to interleave the two power sources. Examination of the circuit shows that IGBT 7 and D7, IGBT 9 and D9, and IGBT 11 and D11 are in parallel and could be replaced with a single IGBT and antiparallel diode (see Fig. 12). The operation of this circuit is possible using the simple switching control subsequently described and would result in a reduction in the switch count. However, independently switching the IGBTs could potentially allow a more advanced switching strategy should space vector modulation be employed.

B. Advantages

The novel power electronic circuit removes the need to use bidirectional dc–dc converters, which contain bulky components. The novel converter is potentially more efficient than an arrangement containing a dc–dc converter by using fewer energy conversion stages .Other power electronic circuit configurations can be used to improve the efficiency by not employing dc–dc converters. However, the circuits proposed either use transformer windings [19] to inject currents or require access to both ends of the traction motor windings [22] and therefore require modifications to traction motors. In addition, Fig. 9 always has two switches per phase conducting, whereas when the converter presented in this paper is fed from the dc traction supply (the normal mode), it has only one switch conducting per phase, thus reducing power electronic losses.

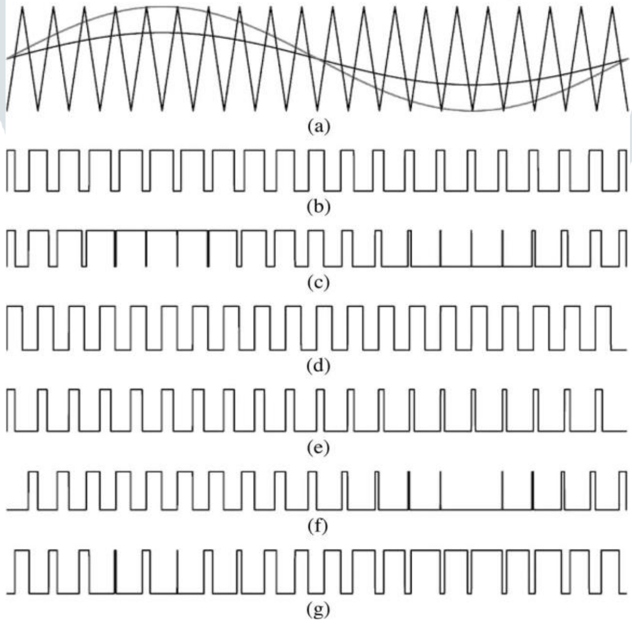

Fig.11. PWM signal generation. (a) Control signals (sine waves) and carrier signal (triangular wave). (b) PWM signal for dc source PWMa. (c) PWM signal for ESS source PWMb. (d) Square wave. (e) Switch control signal for IGBT 1PWMa AND square. (f) Switch control signal for IGBT 7 and IGBT 8PWMb AND square. (g) Switch control signal for IGBT 2(PWMa AND square)OR(PWMb AND square).

Specifically, this converter has the following advantages over the directly fed ac solution previously presented and shown in Fig. 9.

- The converters presented in Figs. 10–12 do not require the use of both ends of the motor windings and can be used with a standard traction induction motor.

- Switch pairs 7/8, 9/10, and 11/12 are in effect a single bidirectional switch. Such bidirectional switch solutions are being developed for, among other applications, matrix converters. Alternatively, 7, 9, and 11 may be replaced bya single switch (see Fig. 12). Both of these solutions result in a lower switch count than Fig. 9.
- If switches 7–12 are discrete devices, then switches 7, 9, and 11 are either fully on or fully off during ultra capacitor-fed mode or mains-fed mode, respectively. Switching losses are thus considerably reduced in these modes compared with conventional PWM switches, unless frequent PWM chopping between these two modes is required.

VI. DRIVE SWITCHING CONTROL FOR DUAL-MODE OPERATION

Even with appropriate design of the traction supply and energy storage unit, the two dc sources will frequently be at significantly different voltages, particularly as the ultra capacitor voltage can vary depending on its state of charge. This requires different modulation constants to achieve the same applied volt seconds. Two switch control signals can be generated: one for the dc supply operation of the converter and one for the energy storage operation of the converter. Each phase has three switches (counting the bidirectional switch as a single switch). However, only one of these switches can be turned on at any instance to prevent short circuits between the dc sources or between one of the dc sources and ground. As an example of an appropriate modulation strategy, two PWM signals are generated for the two modes of operation: 1) standard inverter mode and 2) energy storage source inverter mode. Each PWM signal has two parts: one to control the

TABLE III: Switch Decoding of PWM Signals

Switch	*Signal*
IGBT1	PWM_a AND select
IGBT2	($\overline{PWM_a}$ AND select) OR ($\overline{PWM_b}$ AND $\overline{select}$)
IGBT7	PWM_b AND $\overline{select}$
IGBT8	PWM_b AND $\overline{select}$

switch connecting the circuit to the high voltage source, and the other to control the switch connecting the circuit to ground. The signal to control the low-voltage switch is the inverse of the signal controlling the high-voltage switch. The four signals are denoted as PWMa, PWMa, PWMb, and PWMb, where subscripts a and b denote the two sources. These signals are enabled by two square-wave signals. The two square-wave signals are in anti parallel; these are denoted select and select (see Fig. 13 and Table III). The square wave can be altered, and by controlling the duty cycle, the proportion of time each switch is employed is governed, hence controlling the proportion of energy used from each source.

VII. MODELING THE NOVEL POWER ELECTRONIC CONVERTER

A. Overview

The operation of the proposed power electronic converter can be evaluated through simulation in the PSCAD/EMTDC simulation package, which is a time-domain transient simulator. A 550-V dc source was used as the traction supply. The ultra capacitor was modeled as a 17.8-F capacitor and a 65-mΩ series resistance [6] and charged to 390 V for the simulations. The IGBTs and diodes used the standard PSCAD/EMTDC equivalent circuit model (ON-state, 1-V drop plus 10 mΩ series resistance; OFF-state, a 1-MΩ resistance). The power electronics converter has a switching frequency of 20 kHz, producing a sinusoidal output. As the motor time constants are much greater than that of the power electronics, the motor can be represented as a quasisteady- state equivalent circuit. A vehicle speed of 5 m/s and a traction motor power of 50 kW were selected for the simulation. From the traction model, the motor voltage and frequency are122 V and 24.4 Hz, respectively, at this operating point. To simplify the implementation in PSCAD, the motor is assumed to be in steady state and therefore represented as an impedance of 0.7911 + j0.0863Ω. Using the control strategy described in Section VI, a modulation constant of 0.6274 was found to be necessary for the dc supply branch, and a modulation constant of 0.885 was determined for the ultra capacitor branch, splitting the power derived from the storage and the dc traction supplies. Using the conditions described, the motor current is sinusoidal with a frequency of 24.4 Hz with minimal distortion (see Fig. 13). The current drawn from the ultra capacitor is shown in Fig. 15. The current consists of high-frequency peaks. Averaging over the simulation gives a current of 69.9 A. This represents a power of 27.3 kW. The supply current is also averaged and is found to be 50.1 A, corresponding to 27.5 kW of power. The power electronic converter provides a total of 54.4 kW of power to the motor, split almost equally between the two sources.

B. Detailed Operation

In all three modes of operation (see Figs. 9–13), the motor phase current follows a sinusoidal trajectory with a small amount of PWM ripple. If the ultra capacitor current is drawn [during mixed-mode operation (se e Fig. 13) and capacitor only mode (see Fig. 13)], a small amount of voltage ripple occurs on the ultra capacitor rail voltage, resulting from the iR drop across the ultra capacitor's series resistance. Over an extended period of time, the average voltage also drops as bulk capacitor discharge occurs. Over the period shown in Fig. 13, this is about 1%. The currents through the switches exhibit typical PWM variation.

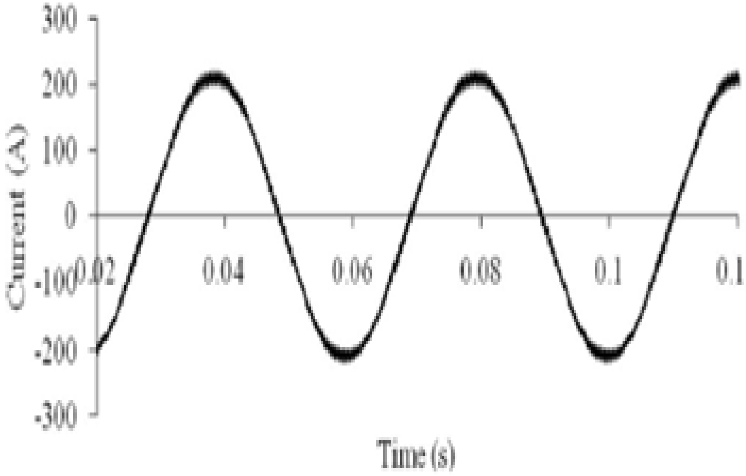

Fig.12. Simulated induction motor phase current during motoring.

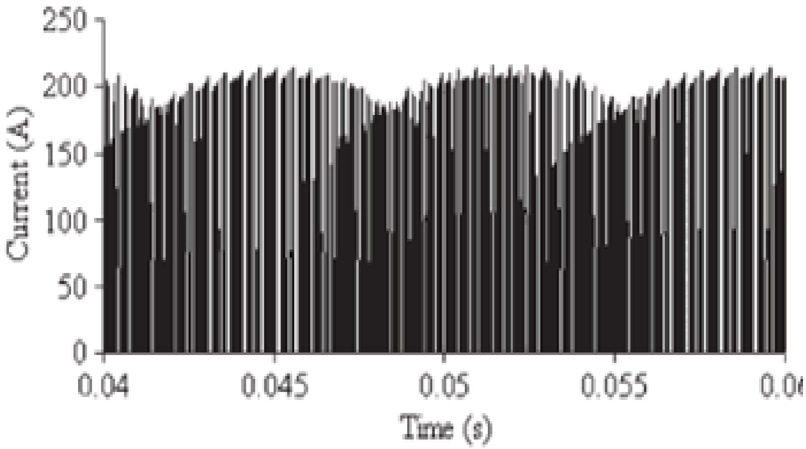

Fig.13. Simulated ultracapacitor current during motoring.

VIII. INCORPORATION OF THE POWER ELECTRONIC CONVERTER INTO THE SYSTEMS MODEL

The system simulation described in Section I and [5] uses a conventional inverter model. To assess the specific impact of this converter on tram operation, the inverter model needs to be modified and storage incorporated. To this end ,the power electronic converter can be approximated from a conduction and switching losses point of view as two inverters in parallel with additional switches. One of the inverters uses switches IGBT 1, 2, 3, 4, 5, and 6, and the other inverter uses IGBTs 8, 2, 10, 4, 12, and 6. IGBTs 7, 9, and 11 are the additional switches. IGBTs 2, 4, and 6 are common to both inverters. In any of the three modes of operation, either inverter A or inverter B operates. For the combined losses in inverters A and B, the losses are equivalent to the losses in a single inverter operating continuously. The converter losses can be determined by adding the losses determined for a single inverter with the losses for the additional switches IGBT 7, IGBT 9, IGBT 11, D7, D9, and D11 (see Fig. 14). The inverter model assumes that current is conducted by the IGBTs rather than the diodes. This simplification is made to ensure that the losses are not underestimated, as IGBT losses are generally greater than diode losses. When considering bidirectional switches, one IGBT and one diode will conduct. When modeling the additional switches, it will be assumed that the diodes are conducting, as it is assumed that the IGBTs are conducting in the inverter model. The diode losses are a function of the current flowing in the model, comprising a fixed diode drop and a series resistance. The energy management system has the following three modes:

- traction power supply mode;
- ESS mode;
- mixed mode (combination of the two sources).

The decision of which mode to use can be made with some simple rules. storage device state of charge has not reached the maximum level. If the ESS has reached a full state of charge, then it is assumed that any additional regenerated energy is dissipated in braking resistors. This function is implemented in the energy storage model. The second part of the energy management system considers Positive power demands. If there is a power demand and the Energy storage device is above a specified charge level, then the energy storage device alone is used to power the vehicle. If the state of charge falls below the specified level SOC upper, a combination of the two sources is used. If the ESS state of charge falls to a minimum level, then all energy is taken from the traction supply system. The vehicle was simulated over the drive cycle for the following three configurations:

- no onboard energy storage;

- energy storage with dc–dc converter;
- energy storage with novel power electronic converter.

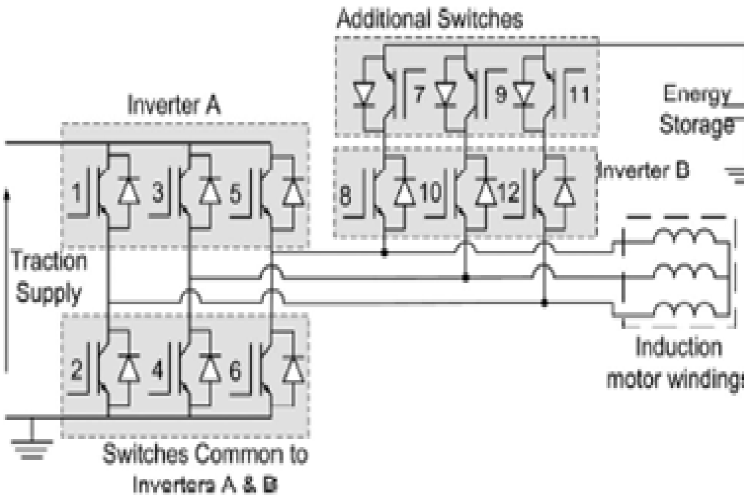

Fig.14. Novel power electronic converter-switch groups highlighted.

These results are simulated in Table IV. Using the results of the simulation with no energy storage as a base case, energy savings can be described as a percentage of the total vehicle energy. Implementing energy storage with a 50-kW converter achieves an energy saving of 0.293 kWh/km, which is an 18% reduction with 100 passengers, and with no passengers, the energy saving is 20%. Using the novel power electronic converter achieves an energy saving of 0.382 kWh/km, which is a 23% reduction with 100 passengers and a 28% energy consumption reduction with no passengers. The results show that significant savings can be achieved by implementing energy storage. The novel converter can save an additional 0.09 kWh/km, i.e., up to an extra 8%, depending on passenger loading.

IX. SIMULATION RESULTS

Simulation results of this paper is as shown in bellow Figs.15 to 19.

A. Simulation Diagram

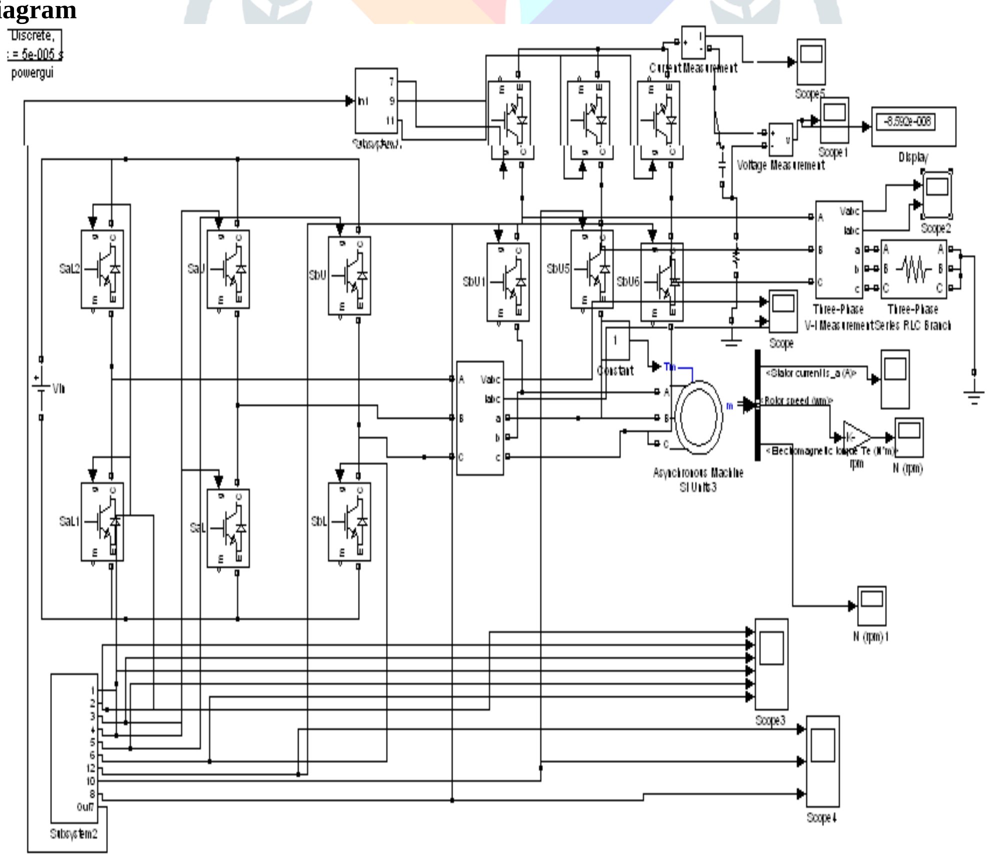

Fig.15. Simulation diagram.

B. Resultant Waveforms

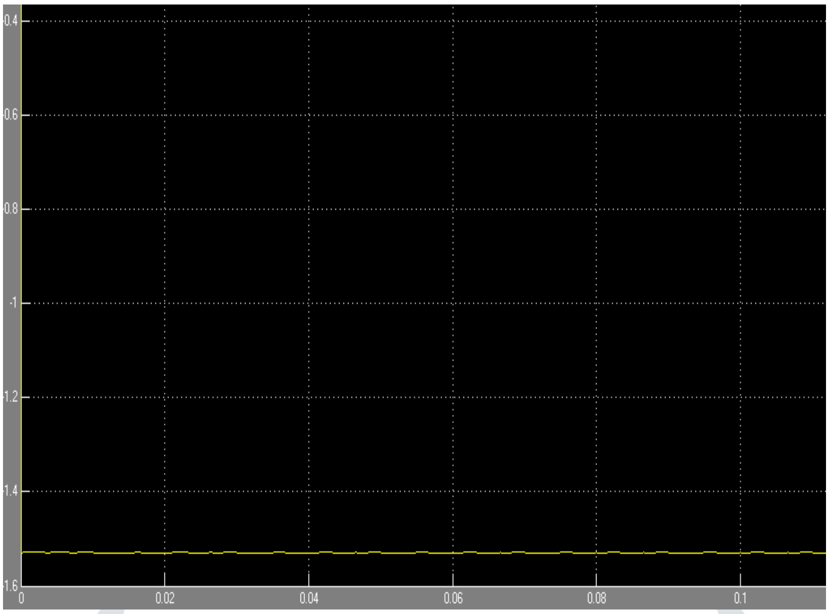

Fig.16. Output current.

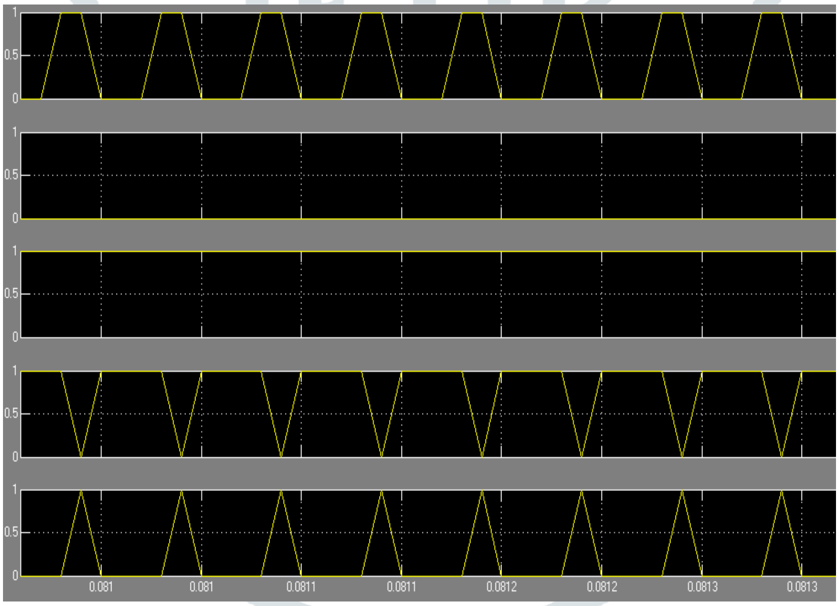

Fig.17. Pulses voltage.

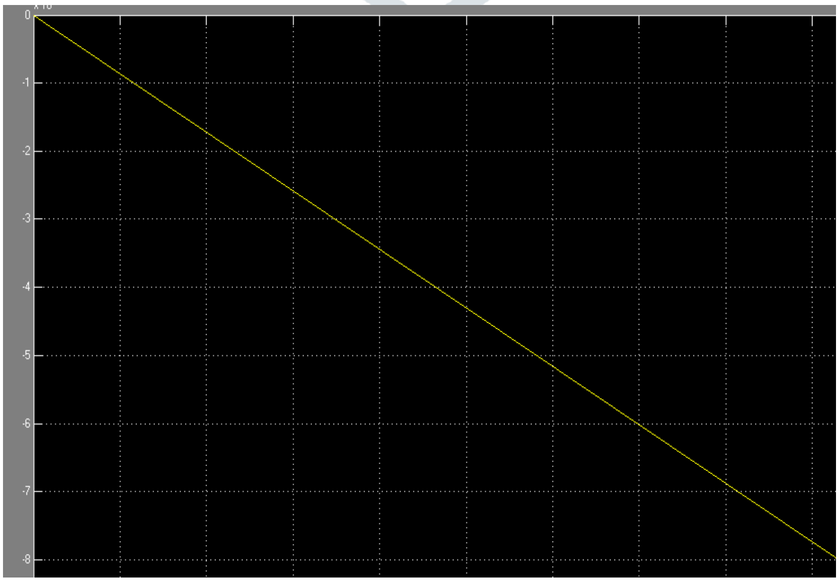

Fig.18. Out put voltage.

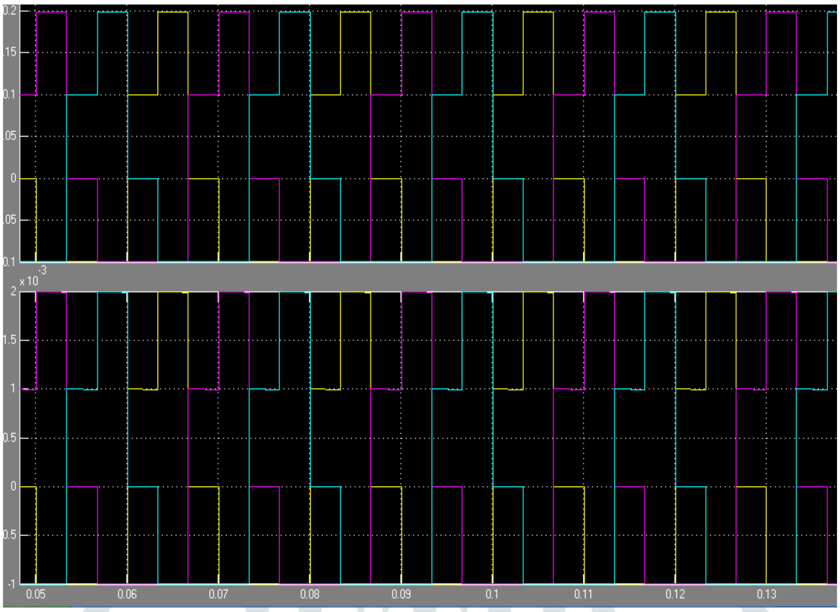

Fig.19. Vabc ,Iabc.

X. CONCLUSION

This paper has presented a new converter topology for light rail traction. The Black pool tram system in the U.K. has been taken as a study case. It has been shown that energy storage on board each tram can substantially reduce energy use per kilometre. A new converter circuit has been presented. It has been shown that further energy savings per kilometre can be achieved with the novel converter as opposed to a conventional power electronics topology. Electrical energy storage has a significant role to play in improving the performance of future electric traction systems. This paper proposes a new power electronics topology that integrates the energy storage power electronics with those of the inverter drive system. This topology reduces weight and component count compared with previous topologies but still allows the use of standard machines. Practical results from a laboratory test system are shown, and indicative energy savings for a full-sized system are presented. A study on a City Class Tram on the public transportation system in Black pool, U.K., shows that clear energy savings may be made by employing ultra-capacitor energy storage with the proposed topology.

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Author's Details:

S.NISCHALA, received the B. Tech. degree in Electrical and Electronics Engineering from PRRM ENGINEERING COLLEGE (JNTU Hyderabad) and M.Tech in Power Electronics from TKR COLLEGE OF ENGINEERING AND TECHNOLOGY (JNTU Hyderabad). She is currently working as a Assistant Professor in Sri Indu Institute of Engineering and Technology. She is working towards the Ph.D. degree in Electrical Engineering. Mail : nish.maya234@gmail.com

G.BHARGAVI received the B. Tech. degree in Electrical and Electronics Engineering from SRI VISVESVARAYA INSTITUTE OF TECHNOLOGY & SCIENCE (JNTU Hyderabad) and M.Tech in Power Electronics from AURORA'S ENGINEERING COLLEGE (JNTU Hyderabad). She is currently working as a Assistant Professor in Sri Indu Institute of Engineering and Technology. She is working towards the Ph.D. degree in Electrical Engineering. **Mail : bhargavi1016@gmail.com**