# Simplified Power Converter for Integrated Traction Energy Storage

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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.

Index Terms—Energy conversion, energy storage, power control, traction power supplies.

## I. INTRODUCTION

With growing importance being placed on decarburizing 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 commute 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) onboard 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.

#### **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 that a systems approach must be taken—maximizing the utility of the storage and minimizing the extra weight added.

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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.



braking speeds (braking speeds of 0.2–1.4 m/s2 in 0.2-m/s2 steps).

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).





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



cycle city tram over a short drive cycle.

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.

# 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 Blackpool tramway will be used.

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# **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/km unloaded (TARE value).

TABLE -I ENERGY CONSUMPTION OF VEHICLE COMPONENTS

COMICILENTS					
	Electrical energy	Electrical energy			
	dissipated (KWh/km)	dissipated			
	TARE (unloaded,	(KWh/km) 100			
	22.5kg)	passengers (29.7kg)			
Friction loss	0.172	0.172			
Motor	0.254	0.395			
Traction	0 191	0 277			
inverter	0	0.277			
Auxiliary	0.133	0.133			
Braking	0.501	0.653			
Total	1.250	1.630			

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 by 0.068 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.

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	Electrical energy dissipated (KWh/km)						
Converter	50Kw DC-DC converter		100kW DC-DC converter				
Passenger load	TARE	100 passengers	TARE	100 passenge rs			
Frictional force	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	0133			
ESS	0.061	0.071	0.076	0.092			
Converter 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			

#### TABLE II ENERGY DISSIPATION WITH ENERGY STORAGE

# 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 trams run 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 a new idea. The development of the Yverdon Gyrobus began in 1945 [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.



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



**Fig. 6. Typical constituents of light rail electrical system.** 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 is essential to minimize the size, weight, and cost of the energy storage conversion system. Bidirectional dc–dc converters have to be sized for peak power level. The "standard solution" (Fig. 5) would use high-power dc–dc converters. These are expensive 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 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]. 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].



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



Fig. 8. Configuration using transformer coils to inject current to the induction motor [9].



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Fig. 9. Dual inverter-fed traction drive [22].

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.

## 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 antiparallel 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).



Fig. 11. Novel converter arrangement—Type 1.

#### 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.

*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 anti parallel 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.



Fig. 10. Source circuit—two inverters connected in parallel.



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Fig. 12. Novel converter arrangement—Type 2.

#### **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.

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

- 1) 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 2) bidirectional switch. Such bidirectional switch solutions are being developed for, among other applications, matrix converters. Alternatively, 7, 9, and 11 may be replaced by a 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, 3) 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 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.



Fig. 13. 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 ANDsquare. (f) Switch control signal for IGBT 7 and IGBT 8 PWMb AND square'. (g) Switch control signal for IGBT 2 (PWMa AND square) OR (PWMb 'AND square').

TABLE III SWITCH DECODING OF PWM SIGNALS

Switch	Signal			
IGBT1	PWMa AND select			
IGBT2	(PWMa' AND select) OR (PWmb' AND select')			
IGBT7	PWMb AND select'			
IGBT8	PWMb AND select'			

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## 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-m $\Omega$  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 m $\Omega$  series resistance; OFF-state, a 1-M $\Omega$ 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 quasi steady 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 are 122 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  $0.7911 + j0.0863\Omega$ .

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. 14).



Fig. 15. Simulated ultra capacitor current during acceleration.

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. 16–18), 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 (see Fig. 16) and capacitor only mode (see Fig. 18)], 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. 18, this is about 1%. The currents through the switches exhibit typical PWM variation.



Fig. 16. Mixed mode operation. (a) Switch 1 current at peak. (b) Switches 7 and 8 current at peak. (c) Capacitor voltage. (d) Motor phase current.



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#### VIII. HARDWARE VERIFICATION

The operation of the power electronic converter was demonstrated and tested by building a physical test rig, connecting the power electronic converter to drive a traction motor (see Figs. 19 and 20). The test rig is built with a 7.5-kW (nominal) induction traction motor mechanically connected to a dynamometer. The power electronic converter is connected to a dc rectifier and an ultra capacitor bank. The test system is controlled using a dSPACE controller. Fig. 19 shows a schematic of the test rig. The motor was driven with a constant-speed dc machine load and operated in V/f control. The tests were performed under constant speed and constant torque conditions and at reduced voltage to validate the operation of the converter (Fig. 22 under lower speed, and higher torque, than Fig. 21). Motoring from both the ultra capacitor (see Fig. 21) and a dual-supply mode, where energy was taken from both (see Fig. 22), is shown. Braking is also shown (see Fig. 23). A near-sinusoidal supply current to the motor was achieved. Some cross-over distortion is clearly evident, although the principle of operation of the new circuit is shown to work.

## IX. INCORPORATION OF THE POWER ELCECTRONIC 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 One of view as two inverters in parallel with additional switches. of the inverter 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. 24).

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.





Capacitor voltage. (d) Motor phase current

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Fig. 19. Experimental test system layout.





Fig. 23. Motor current—ultra capacitor braking, 100-V dc supply, capacitor charged to 70 V.

The energy management system has the following three modes:

- Traction power supply mode; 1)
- 2) ESS mode;
- 3) Mixed mode (combination of the two sources).

The decision of which mode to use can be made with some simple rules.

The first rule is that, for negative power demands, i.e., regenerative braking, only the energy storage unit is connected so that all the energy goes to the ESS, provided that the energy 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 SOCupper, 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:

- 1) No onboard energy storage;
- 2) Energy storage with dc-dc converter;
- 3) Energy storage with novel power electronic converter.



Fig. 24. Novel power electronic converter—switch groups highlighted.

TABLE IV				
Simulation results for city class tram with and without				
energy storage, empty, and with 100 passengers				

energy storage, empty, and with roo pussengers						
	No Energy storage (KWh/km)		Energy storage with 50kW converter kWh/km		Energy storage with novel power electronic converter kWh/km	
	TAR E	100 pass	TARE	100 pass	TARE	100 pass
Fiction	0.172	0.172	0.172	0.172	0.172	0.172
Motor	0.254	0.395	0.257	0.399	0.257	0.399
nverter	0.191	0.277	0.193	0.280	0.233	0.335
ESS	0.000	0.000	0.061	0.071	0.000	0.000
Converte r ESS	0.000	0.000	0.029	0.036	0.048	0.092
Braking	0.501	0.653	0.151	0.247	0.060	0.125
AUX	0.133	0.133	0.133	0.133	0.133	0.133
TOTAL	1.250	1.630	0.997	1.337	0903	1.248

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%.



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Using the novel power electronic converter achieves an energy saving of 0.382 kWh/km, which is a 23% reduction with 100 passengers and 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.

#### X. CONCLUSION

This paper has presented a new converter topology for light rail traction. The Blackpool tram system in the U.K. has been taken as a study case. It has been shown that energy storage onboard each tram can substantially reduce energy use per kilometer. A new converter circuit has been presented. It has been shown that further energy savings per kilometer can be achieved with the novel converter as opposed to a conventional power electronics topology.

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