ELECTRIC DRIVE FOR FLYWHEEL ENERGY STORAGE

S. C. TRIPATHY†

Centre for Energy Studies, Indian Institute of Technology, Hauz Khas, New Delhi-110 016, India

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Abstract—This paper presents the results of experimental work on flywheel energy storage systems for city buses. An efficient electronic hardware scheme is used to start the flywheel and traction machines. This scheme has been designed, fabricated and tested in our laboratory. A low frequency a.c. has been derived from an inverter fed from a three-phase uncontrolled rectifier to start the commutatorless d.c. motors. Commutation is achieved by using a capacitor and two auxiliary thyristors, whose ratings could be a fraction of full machine ratings, as they are needed during starting only. The frequency of the inverter output is controlled by a function generator. For successful commutation in all modes of operation, a capacitor voltage sensor circuit has been employed.

Energy storage  Inverter  Commutatorless motors

INTRODUCTION

In the flywheel energy storage system, to decelerate the vehicle, an electromagnetic torque (braking torque) is applied to the rear wheels of the vehicle. The kinetic energy of the vehicle is used to do work against this opposing torque, and this work is converted into electrical energy. To develop this opposing electromagnetic torque, a generator is used with the rear wheels as a prime mover. This developed electrical energy is converted into mechanical energy by using a motor at the flywheel. This mechanical energy is stored in the flywheel. For accelerating the vehicle, the mechanical energy stored in the flywheel is converted into electrical energy by using a generator. This electrical energy is converted into mechanical energy by a motor and is used for accelerating the vehicle. When the flywheel is discharged to a low speed, the internal combustion engine takes over the control and provides the required power for further acceleration. In this way, the amount of fuel consumed is saved. In the next stopping operation, the flywheel will be charged again and will produce energy for the next acceleration. Even so, the fuel saved through this type of complicated operation is small for a single start–stop cycle. When this value is integrated over a complete day, it will be of considerable amount. If the complete fleet of vehicles is considered, the fuel expenditure will be heavily reduced.

THE SELECTION OF ELECTRIC MACHINERY

The electric transmission system for the hybrid vehicle [1] requires two machines and associated power controlling equipment. These machines must be capable of (1) generating energy by converting from mechanical energy to electrical energy and (2) motorizing by recovering electrical energy to mechanical energy. Separately excited d.c. machines are capable of these modes of conversion when armatures of two of these motor generators are connected electrically together. The entire control process can be accomplished by the coordinated, separately excited field control of the two machines.

The advantage of using d.c. machines is the light weight, simple power control equipment, but on the disadvantage side, the mechanical commutator imposes restrictions on rotational speeds, the electrical loading and the operating environment of the d.c. electrical machine. This is because of structural, thermal wear and sparking considerations of the mechanical commutator. The d.c.

†Present address: Department of Electrical and Electronic Engineering, Middle East Technical University, Inonu Bulvari, 06531 Ankara, Turkey.
machine cannot be operated at flywheel speeds nor can it be operated within the low pressure flywheel chamber. A speed reducer between a flywheel and the commutator machine requirement is also a problem. The machine is also heavy.

By using solid state devices as a supplement of this mechanical commutator, a smaller directly driven, hermetically sealed flywheel machine can be considered. The flywheel cavity may contain helium or hydrogen for cooling at 1 psia.

THE SYSTEM SIMULATION

The complete behaviour of the flywheel energy storage system mainly depends on the flywheel speed and inertia. The rate of charging and discharging of the flywheel depends upon the deceleration and acceleration of the vehicle. The machines associated with the system are considered as d.c. machines. In d.c. machines, the load torque depends on load current and field current. The field current, in turn, controls the back e.m.f. of the motor and the output voltage of the generator in accordance with their speed. In actual operation, the speed of the flywheel decreases while the vehicle is accelerating, and the flywheel speed increases while the vehicle is decelerating. The field currents must be so adjusted that they should take into account these speed relations and, at the same time, should control the energy transfer.

The system's economic feasibility depends on the fuel savings that this system can provide. The main aim of this project is evaluation of the fuel savings. This can be accomplished by comparing the fuel consumption of two vehicles, one with a flywheel energy storage system and the other without any flywheel energy storage system.

The main data input to the simulation programme is the driving cycle. It is a time vs. velocity plot of a bus. To get the driving cycle, a survey has been conducted for a complete day on a Delhi Transport Corp. (DTC) bus running on route from Munirka to Plaza. The DTC officials helped by providing an extra speedometer, and it is so placed that it is visible from the first passenger seat, just behind the driver. With the help of this speedometer, a digital watch and a cassette recorder, the readings of the speedometer have been recorded for every 5 s. This type of recording has been carried out throughout a complete day for a total of six trips. Later, graphs have been plotted with these readings. From these plots, one driving cycle has been selected for the simulation. To determine the transmission gear ratio, the engine tone has been recorded. From the engine tone, the shift points have been determined. The DTC officials also helped in obtaining the vehicle's physical and mechanical data.

Two d.c. machines are assumed for the simulation. Their output voltage, power, speed and field current are all assumed. All these assumptions are in practical limits. A computer programme has been developed in FORTRAN IV on an ICL 2960. Two flywheels have been considered with the same energy but with different speeds and inertias. It has been tried to evaluate the parametric behaviour of the system with these two different flywheels for the same driving cycle.

THE DRIVES OF THE SYSTEM

The flywheel, as well as the traction machine, may be either a d.c. motor or a d.c. driven a.c. motor. In the latter, it has been called as 'commutatorless d.c. motor'. It possesses all the flexible characteristics of a d.c. motor and without any mechanical commutator problems. But, this type of machine is not a self-starting machine unless shaft position sensor signals can be derived even in the motor stand still condition.

Two schemes have been already developed for the starting of the machine. In one scheme, a shaft position sensor has been used in an indirect way, and the commutation of the main inverter thyristors has been achieved by using a capacitor and two auxiliary thyristors have been used in lower speeds of the motor. This scheme enables the motor to work as a commutatorless d.c. motor. In the second scheme, during the starting and low speed periods, the commutation is achieved by interrupting the d.c. link current six times per cycle. A low frequency a.c. has been derived from the inverter and is used in starting the machine. Once the machine reaches considerable speed, rotor sensor signals have been derived from sensing the motor terminal voltages.
In the new scheme developed in this paper, both the above two schemes have been combined. A low frequency a.c. has been derived from the inverter, but the d.c. voltage source is a three-phase uncontrolled rectifier. So, there is no possibility of interrupting the d.c. link current without using an extra converter (d.c.–d.c.). So, in this new scheme, commutation is achieved by using a capacitor and two auxiliary thyristors as in the case of the first scheme. The ratings of the capacitor and the two auxiliary thyristors can be a fraction of the full machine ratings, as they are in need of use during starting only. The frequency of the inverter output is controlled by a function generator from which the reference pulses have been derived. For successful commutation in all modes of operation, a capacitor voltage sensor circuit has been employed.

The motor has been started with an input of 1 Hz a.c. with a reduced d.c. voltage. Once the motor (synchronous) synchronizes with this frequency, both the frequency and the d.c. voltage have been increased slowly till the motor reaches 300 rpm. The speed of 300 rpm is sufficient to load commutate the inverter main thyristors, and the motor terminal voltage can be used for generating synchronizing pulses for the inverter. The later case is out of the scope of this paper.

**SYSTEM TYPES**

This work documents the investigation of a heat engine/flywheel hybrid propulsion configuration that employs an electrical transmission in addition to the existing heat engine to transfer energy between an energy storage device and the vehicle. The basic electrical transmission system is shown in Fig. 1.

There are three types of transmission system options

<table>
<thead>
<tr>
<th>Type</th>
<th>Flywheel input/output machine</th>
<th>Traction machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>d.c.</td>
<td>d.c.</td>
</tr>
<tr>
<td>2</td>
<td>a.c.</td>
<td>d.c.</td>
</tr>
<tr>
<td>3</td>
<td>a.c.</td>
<td>a.c.</td>
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In this project work, only the d.c.–d.c. system is under investigation.

The primary use of any transmission system is to augment the heat engine with energy from the flywheel in such a way as to level engine loads and improve the overall vehicle efficiency. The benefits of using this hybrid system are as follows:

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**Fig. 1. Basic scheme.**
(1) Provides fuel economy which is not possible with any other conventional propulsion arrangements.
(2) There will be a reduction in contribution to pollution as the fuel consumption is reduced.

THE TECHNICAL APPROACH

Figure 2 is the basic structure of the total system of the heat engine (HE)/flywheel (FW) hybrid propulsion configuration, and the HE and FW simultaneously supply power to the rear wheels of the vehicle. Power can be supplied both from the HE and the FW simultaneously or either only from the HE or FW. When the HE is alone supplying power, the electrical transmission system can be cut off.

To explain the operational behaviour of the system we start with the assumption that the FW is at rest. The traction machine (TM) motor/generator (M/G) system acts as a generator. It converts the mechanical energy from the HE to electrical energy, and this electrical energy is fed to the FW M/G system. The FW M/G system, now acting as a motor, converts the input electrical power into mechanical power.

This developed mechanical power is used to rotate the FW and is stored in the FW as it gains speed. This mode of FW charging operation continues until the FW attains about 150% of the rated speed.

The next mode of operation is the acceleration of the vehicle (bus). In this mode of operation, the FW M/G system acts as a generator, and the traction machine M/G system acts as a motor. With the FW acting as the prime mover, the FW M/G system generates electrical power, and this
power is fed to the TM. It converts this power into mechanical power, and this mechanical power accelerates the vehicle.

The accelerating mode, in which the total required power is supplied completely by the FW, continues until the FW discharges to approx. 50% of the initial speed. Then, the HE will be turned on, and the required power will be split between the HE and FW. The ratio of this power split will be such that the HE operates in its low SFC region. Once the FW discharges to 25% of the initial speed, the HE supplies the total required power alone. By this time, the bus reaches a considerable velocity state.

In the third mode of operation, the kinetic energy of the moving vehicle is to be transferred to the FW. The TM M/G system, acting as a generator, and the jack shaft of the vehicle, acting as the prime mover, convert the kinetic energy of the vehicle into electrical energy. This electrical energy is fed to the FW M/G system, now acting as a motor. This converts the electrical energy input into mechanical energy. This mechanical energy accelerates the FW, and hence, it will be charged. This stored energy is reused in the next acceleration mode of the vehicle.

A complete scheme of a.c. machines (induction or synchronous) cannot be used in the flywheel energy storage system due to the difficulties associated with their control circuits. In both the cases (induction or synchronous), the speed can be smoothly varied by varying the frequency of the input a.c. power or in steps by pole changing. As the flywheel motor has to be converted to a generator during the acceleration period of the bus wheels, although synchronous machines are suitable, their speed control is a difficult problem. The best option for the flywheel drive is a d.c. power driven a.c. machine, called 'commutatorless d.c. motor'. By using this special motor, the total assembly of the flywheel can be kept in a vacuum chamber to reduce windage losses. This type of motor can also be used in battery operated vehicles. In these motors, the mechanical commutator of a d.c. machine is replaced by a solid state commutator.

**TECHNICAL APPROACH**

An inverter driven synchronous motor can be operated as a commutatorless d.c. motor. In a static variable frequency drive using a synchronous motor, the inverter output frequency is determined by a highly stable reference oscillator which is independent of the load [4]. If the gating of the static inverter is controlled by a position transducer on the rotor shaft, the synchronous motor is endowed with the flexible variable speed characteristics of a d.c. machine. The static inverter and the position transducer on the rotor shaft can be regarded as a solid state commutator which performs the function of a mechanical commutator. Transistors can be used as switching elements for small motors, but thyristors are necessary for large motors.

Conventional d.c. armature windings may be used with solid state commutators which simulate the progressive switching action of the multi-segment mechanical commutator. These machines may be operated as commutatorless d.c. motors by fitting a d.c. excited field system and controlling the thyristor switching from the rotor shaft. The armature winding and solid state commutator establish an air gap magnetic field which rotates synchronously relative to the armature, as in the polyphase a.c. machine. Consequently, any standard form of rotor, permanent magnet rotor or reluctance rotor may also be fitted.

The commutatorless d.c. motor has also some practical drawbacks, the same as those of a synchronous machine. The main problem lies in starting the machine. In a synchronous motor, torque is produced due to the interaction between the rotating magnet field and the d.c. magnetic field. The armature produces a rotating magnetic field in synchronism with the supply frequency. The main problem with these machines is the initial locking of these magnetic fields. Due to the high relative velocity between the field MMF wave and the armature MMF wave and at the same time due to the high inertia of the rotor, magnetic locking is not possible initially. Hence, the machine is not self-starting. In conventional methods, the machine is driven by another d.c. or induction machine to the synchronous speed, and then the necessary magnetic locking is obtained.

**VARIOUS STARTING SCHEMES**

In an unconventional way, the commutatorless d.c. motor can be started by generating firing pulses to the inverter from a shaft position sensor. In the beginning of the work on the
commutatorless d.c. motor, reference signals were derived from magnetic pick up coils wound on a 'U'-shaped laminated core. As the magnet moves away from the pick-up coils, there is a decrease in the flux linkage, and an e.m.f. of opposite polarity is induced. As the magnet moves toward the pick-up coils, there is an increase in the flux linkage, and an e.m.f. is induced in the coils. This induced e.m.f. gives the information about the rotor position, thus deriving the synchronizing pulses. In this method, the output from the pick-up coils decreases with speed and cannot be used for locating the position of the shaft for starting. At the same time, at high speeds, the generated e.m.f.s may exceed the maximum safe rating of a thyristor. Alternatively, the motor has been started by applying an external triggering source which automatically changes from low to high frequency. The output from the pick-up coils is so low at lower frequencies that it is impossible to synchronize the externally applied switching source until the machine speed reaches a reasonable value. This results in uncertain starting.

For reliable starting, it is necessary to know the shaft position even when the motor is stationary. For this purpose, if Hall devices are used, a carefully designed magnetic circuit is necessary. Photoelectric devices also can be used for starting. If this is the case, there will be portions on the shaft in which a photo-cell will be half against the reflecting and half against the non-reflecting sides of the rotor. If this motor comes to rest in this position, it would cause firing of both thyristors of any leg in the inverter when the motor is restarted, eventually short circuiting the supply. Hence, this is also not a perfect method. In another way, a cyclo-converter can be used for starting. A cyclo-converter cannot be operated from a d.c. source. Even with an a.c. source, for conversion of three-phase fixed frequency a.c. source to three-phase variable frequency source, a total of 18 thyristors are necessary. This is not an economical way of starting.

The second drawback of a commutatorless d.c. motor is the relative expense of a forced commutated inverter relative to their a.c.-a.c. or d.c.-d.c., converter counterparts. When employing a synchronous motor, the field winding can be over-excited such that a leading power factor is presented to the inverter. In this case, natural or load commutation of the inverter thyristors can be obtained. Load commutation considerably simplifies the inverter and is a highly desirable mode of operation [3]. In this load commutation, commutation currents from one thyristor to another are achieved by the generated e.m.f.s of the motor, thus obviating the need for forced commutation. If the motor e.m.f.s are used for commutation of the inverter thyristors, then the inverter must be current fed, and this necessitates the use of large link inductance. From sensing the motor terminal voltages, synchronizing pulses can be derived, thus avoiding the use of either magnetic or optical sensors. Such a drive cannot be operated at low speeds where the machine counter e.m.f. is insufficient to commutate the inverter thyristors. Some forced commutation circuit must be employed in the low rpm region.

One technique [4] which has been used to commutate the inverter at low speeds is to interrupt the d.c. link current by proper control of the phase controlled rectifier feeding the inverter. Since the phase controlled rectifier must drive the d.c. link current to zero six times per cycle, this can be used relatively at low motor speeds. When operating from a d.c. source, such as a battery in the case of a battery operated vehicle, a forced commutated chopper circuit must be used. This scheme fails when there is neither a phase controlled rectifier nor a chopper.

THE NEW SCHEME

The new starting scheme developed in our project is a mix of two schemes [4, 5]. In this scheme, an uncontrolled three-phase rectifier and no chopper circuit are employed. The motor is started as an ordinary inverter driven synchronous motor with a low frequency supply derived from the inverter. Once the rotor attains considerable speed [5] (e.g. 60 rpm), then the motor terminal voltages can be sensed to derive the synchronizing pulses. Changing the mode of operation into a commutatorless d.c. motor is not considered here.

In the motor stand-still condition, the inverter is fired from a stable and controlled oscillator, starting from a low frequency. Once the motor starts and synchronizes to this frequency, both frequency and voltage are simultaneously increased. This operation continues until the motor reaches the required rpm. For commutation of the inverter thyristors, in this starting scheme, a
forced commutation circuit [4] using one capacitor and two auxiliary thyristors is employed. As this forced commutation circuit is in use during starting and bringing the motor to the required rpm, its ratings can be a fraction of the main thyristor ratings.

**POWER CIRCUIT**

The power circuit has been shown in Fig. 3. The circuit utilizes a single commutation capacitor and only two auxiliary thyristors for the entire inverter. Since the forced commutation part of the inverter need operate where the inverter is unable to load commutate, the rating of the circuit components need only be a fraction of full machine rating. It can be noted that the commutation capacitor is connected to neutral of the machine. Since the fundamental component of the commutation capacitor current is three times the inverter fundamental frequency, an inverter employing this scheme may be termed as a third harmonic auxiliary commutated inverter [4].

Figure 3 shows a simplified version of the drive system to be considered. In the system, a d.c. link current $I_d$ is fed to a three-phase inverter which, in turn, drives a synchronous machine. The voltage source is an uncontrolled three-phase rectifier. The link current can be adjusted by varying the input voltage to the uncontrolled rectifier through an autotransformer. In some practical cases, such as traction or battery cars, the voltage source can be any type of a.c.–d.c. rectifier or d.c.–d.c. chopper. The inverter main thyristors T1–T6 are gated sequentially in number. The firing pulses are derived from a ring counter. The machine field current is also controlled by controlling the input to another three-phase uncontrolled rectifier. Since the field current is controllable, the power factor can be controlled. This power factor concept comes into the picture in load commutation and is not discussed here.

![Diagram](image)

**Fig. 3. Power circuit.**
RING COUNTER

The main aim is the production of low frequency voltage, and at the same time, the main inverter thyristors of Fig. 3 have to be fired sequentially as numbered. So, an electronic circuit is necessary which can produce the sequential pulses in accordance with the frequency of an input clock. This can be realized by a 'Ring Counter'. In a ring counter, at any instant, only one output level will be high and the rest will be low.

A shift register can be modified as a ring counter by connecting the last bit to the serial input. When power is switched onto the ring counter, the outputs will be randomly high and low. By giving a negative pulse to the clear terminal, all the bits can be cleared. As the sixth bit is connected to the serial input, it will also be at state 0. The first clock pulse transfers this 0 level to the first bit, and the succeeding clock pulses shift the same 0 level around the ring. This operation goes on indefinitely. But there is no required state 1. To ensure the required state 1 in the ring counter, when the ring counter has been cleared, the serial input must be at state 1 in the ring counter and the first clock pulse shifts this 1 level to the first bit, and succeeding clock pulses shift this state 1 around the ring. The output frequency depends on the input clock frequency. The series input has to be at state 0 through the operation, except when the sixth bit is at state 1. This can be realized by using OR gates and an inverter. The complete logic circuit is shown in Fig. 4.

All six output bits are ORed, and the final output of these OR gates is inverted coupled to the serial input through another OR gate G7. The second input to the G7 is from the sixth bit of the ring counter. When the ring counter is cleared, the output of II will be at state 1. Hence, the serial

Fig. 4. Ring counter.
input is also at state 1, and for the rest of the time, the output of I1 will be at state 0. When the sixth bit is high, the serial input will be high, and the ring counter operation goes on indefinitely. The outputs from the ring counter are fed to the triggering circuits of corresponding thyristors. The clock pulses are derived from a function generator. The frequency can be controlled, and hence, the inverter frequency also can be controlled.

FIRING OF AUXILIARY THYRISTORS

It has been mentioned earlier that the main thyristors and corresponding auxiliary thyristors have to be fired simultaneously. The outputs from the first, third and fifth bits of the ring counter are ORed, and the output of this OR gate is fed to the triggering circuit of Tp. Similarly, the outputs from the second, fourth and sixth bits of the ring counter are ORed, and the output of this OR gate is fed to the triggering circuit of Tn.

THE TRIGGERING CIRCUIT

The trigger circuits of T1–T6 are of the same design, and one is the replica of the other. So, it is sufficient to discuss one triggering circuit, shown in Fig. 5.

As shown in Fig. 5, the output of G23 will be at state 1 if and only if both inputs of G23 are at state 1. This condition will be satisfied if the trigger circuit receives both the capacitor sensor signal and the ring counter reference signal. When this happens, G23 will be enabled, and its output is coupled to G24. When G23 is enabled, G24 also is enabled, and its output will follow the other input, i.e. the carrier wave. The carrier wave is a high frequency (10 kHz) clock generated from an IC-555 timer. The output of G24 will be at 10 kHz if both the inputs to G23 are high. G24

Fig. 5. Triggering circuit.
cannot give the required load current or gate current to trigger the SCR. A current amplifier has been employed to overcome this problem.

The output of G24 is fed to the base of Tr1 through the biasing resistance R29. The trigger transformer T is employed in the collector circuit of the Tr1. When the base of Tr1 receives the carrier wave, the primary of T will be energized which, in turn, will induce e.m.f. in the secondary of T. The biasing resistance and supply voltage to Tr1 should be carefully designed so that the required gate current and gate voltage of the SCR have been induced. For improved operation, the reactive energy of the transformer T also has been used. A free-wheeling diode D3, in series with a resistance R30, is used to circulate the inductive energy stored in the trigger transformer when the carrier pulse is low.

In the secondary of T, diodes D4 and D5 are used for rectification of the induced voltage and to block negative pulses from reaching the gate of the SCR. Resistances R31 and R32 are used as a potential divider to keep the gate current and voltage within the time limits of the gate ratings of the SCR.

In any inductive load circuits, the current does not transfer to the incoming thyristor immediately as the SCR is fired. To avoid this problem, the triggering circuit has to be energized until the current in the SCR becomes more than the latching current. To design the trigger transformer for this purpose, as well as for isolation between the power circuit and control circuit, as the firing frequency is low, is a big problem. To avoid this, a high frequency carrier wave has been modulated by the reference pulses.

**OBSERVATIONS**

**Starting of the motor**

By giving a negative pulse to the ring counter clear terminal and to the flip-flop set terminal, the initial conditions can be realized. The inverter output frequency has to be carefully adjusted so that it will give a starting a.c. power of 1 Hz. At this frequency, the d.c. link voltage has also to be carefully adjusted. With some initial adjustments, the motors can be started by giving the required negative pulse to the electronic circuitry. Once the motor has picked up the speed and synchronized with the 1 Hz supply, the inverter input frequency and the d.c. link voltage simultaneously have to be increased until the motor reaches 300 rpm. Now, the motor terminal voltages are almost sinusoidal. These terminal voltages can be used for deriving the necessary synchronizing firing pulses to the inverter and for natural commutation. Then, the inverter driven synchronous motor simply becomes a commutatorless d.c. motor.

**Synchronous motors and inverter**

The synchronous motor chosen for the study corresponds to a 7.5 kVA, 10 A 220/415 V, 4-pole machine. The motor rated speed is 1500 rpm, corresponding to a line frequency of 50 Hz. The armature resistance and inductance per phase are respectively 1.1 Ω and 10 mH.

<table>
<thead>
<tr>
<th>Inverter d.c. link parameters</th>
</tr>
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<tbody>
<tr>
<td>Thyristor Converter type</td>
</tr>
<tr>
<td>25 A (rms), 1000 V-PIV</td>
</tr>
<tr>
<td>Capacitor Oil and paper</td>
</tr>
<tr>
<td>160 (10 × 16) F</td>
</tr>
<tr>
<td>d.c. link Inductance</td>
</tr>
<tr>
<td>0.36 mH</td>
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**Observed wave forms**

The photographs show the waveform oscillograms at various points in the inverter. The input frequency to the motor is 10 Hz corresponding to a speed of 300 rpm.

The motor terminal voltages are almost sinusoidal (Fig. 6). Notches in the phase voltage now occur in pairs corresponding to Turn ON and Turn OFF in the auxiliary thyristors. Six notches can be observed, corresponding to the firing of six inverter thyristors for one cycle of output or 180° mechanical revolution of the motor.

The thyristor current wave form has been shown in Fig. 7. The ripples appear in the current wave form corresponding to the commutation period. The conduction period is slightly less than 120°.
In Fig. 8, the thyristor voltage waveform has been shown. In Fig. 9 the capacitor voltage waveforms have been shown. The waveforms are rectangular in shape. The linear charging and discharging can be observed. In the limiting case, the currents in the auxiliary thyristors are each ON for half time and the capacitor voltage becomes triangular. All the waveforms are taken with a finite link inductance of 0.36 mH.

CONCLUSIONS

The flywheel energy storage system is very useful for conservation of energy. In this work, study has been done regarding the system, where it has been considered for a city bus. The system is also useful for battery cars, suburban electric trains and also any heavy machines or, in general, to any system which is subjected to frequent starts and stops.

The main attraction of the system is the flywheel. By designing it properly, fuel savings up to 50% can easily be achieved. In the work so far discussed here, there are assumptions and approximations which are the main reasons for achieving only 35.5% fuel savings. Practically, electric machines with high efficiency may not have an efficiency figure as low as 85%. It may be more than that.

The commutatorless d.c. motor is one of the best options for an electric drive. In this work, the emphasis has been given to the motor starting problem only and that too in relation with the flywheel energy storage systems. But it is useful for other purposes also. In battery cars, even without employing this system, the same drive can be used as the main transducer from electrical
power to mechanical power. It can be operated at high speeds, as it does not have any constraints imposed by the mechanical commutator.

It has been proved that the motor need not be started as a commutatorless d.c. motor, it can be started as an inverter driven synchronous motor and then can be modified into the commutatorless d.c. motor mode.

REFERENCES