Hybrid-Electric Vehicle Designed for Slow, Start/Stop, Low-Gear Driving in Heavy Traffic Conditions in Manila

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Abstract - **This HEV is designed to improve the overall thermal efficiencies of passenger utility vehicles that operate under heavy traffic conditions in the streets of Manila. The system is scalable from a small "passenger tricycle" to a passenger bus and may be considered as a retrofit system to existing vehicles.**

Indexing Terms **- hybrid-electric, variable frequency, variable voltage, sinusoidal inverter, battery charger, regenerative braking, kinetic, potential, energy, fuel consumption, pollution, retrofit, global climate, heavy traffic, switching, deep discharge, charge level.**

I. INTRODUCTION

Driving a vehicle in heavy traffic conditions of a big city like Manila simply wastes fuel and valuable foreign exchange as well as releases unwanted pollutants into the environment. The development of a hybrid-electric vehicle technology would, obviously, set improvements into motion. The implementation of this technology became an attainable goal, when, on October 6, 2003, an experiment to build a 3-phase sinusoidal variable frequency, variable voltage inverter became a success.

For the project to make sense in a developing country like the Philippines, engineers at the Ateneo de Manila University decided that the design must choose components that are available in the local market instead of using parts that must still be imported. This decision supports the goal that the resulting HEV must be scalable to diesel-burning passenger vehicles and buses that are assembled in local shops. On this basis, retrofit work for existing units also become a realizable goal.

That said, though, optimized components such as state-of-the-art motors and other components will be considered in time. For now, it is admitted that there will be a trade-off in terms of resulting efficiencies than if optimized components were used.

The project may be better understood by way of an example. On a typical day, it might take a driver anywhere between 45 minutes to one hour to traverse a 6-mile distance to work. That is a speed of between 6 to 8 mph. The mileage of the car in our example is 15 miles to a gallon on this particular stretch. In contrast, it attains 46 mpg on the highway. It then becomes clear that the amount of pollutants that are released to the environment is significant. If this condition happens in an efficiently designed 1.6-liter engine, the conditions would be worse for non optimized conventional designs, and more for the 2-stroke cycle ones.

Numerous studies [1], [2], [3], [4], [5] have discussed the pollution caused by 2-stroke cycle engines of home-grown tricycles, and of conventional 4-stroke cycle engines in vehicles.

The *A-Trike* ("A" means Ateneo), as the HEV prototype is called, is homegrown, and is built from the ground-up. It was started at the Ateneo laboratories in November of 2002, and today, enjoys US Patent Pending status. The variable frequency 3-phase inverter (VFI) has passed its full functional and safety tests and with this development, the *A-Trike* is scheduled to operate for the first time using electric power in early August 2005.

Since the system is *scalable*, it could be built into locally assembled passenger jeepneys and buses, and would become a retrofit system for older, more inefficient engines to radically reduce consumption of automotive fuel. These retrofits are technically doable, since local engineers, technicians and mechanics assemble these passenger vehicles from surplus engines, transmissions, steel beams, and other components sold and/or fabricated in the local market.

As a spin-off, each of the modules developed here has commercial potential on its own in manufacturing and process automation systems. For example, the VFI can be used for variable-speed conveyors, variable-flow pumps, variable torque applications, and soft-starters for AC motors, to name a few. Renewable energy resources and decentralized energy systems (DES) that use storage batteries could also benefit from this VFI. The system used for charging its series-connected batteries are immediately suitable for use in large station batteries of power plants, communication installations, and others. Its general-purpose "controller-

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dispatcher", when treated like a black box will be able to communicate with the outside world through its *industry-standard* input/output (I/O) ports, making any vehicle a candidate for a retrofit.

II. OVERVIEW OF THE TECHNICAL ISSUES

This section discusses the interaction of the technical issues that led to the selection of the various components, the formulation of the design philosophy, and the evaluation of the consumption of fuel of vehicles participating in a "path caravan."

The initial *A-Trike* vehicle is fitted with a battery storage capacity that can deliver the power requirement of a 1-kilowatt three-phase induction motor for a substantial period of time. While the electric motor is running, the 2.4-horsepower engine is completely shutdown. During this time, however, the conditions of the 12-volt 7-AH batteries are monitored to prevent a deep discharge condition in any one of the seven series-connected batteries. A deep discharge in any battery triggers an alarm. In the extreme case that the condition persists, the battery management system is empowered to shutdown the variable frequency inverter, which would, in turn, shutdown the motor. The generator is a 90-ampere 3-phase automotive alternator. Its diodes have been disconnected so that custom-designed step-up transformers could be installed to serve the purpose of the charging system.

An 84-volt DC system has been chosen in order to minimize the risk to passengers. Transformers are used to bring the operating AC voltage to 230 WYE with a grounded neutral. All the transformers and inductors have been designed and built by local engineers and shops, following the specifications given for the *A-Trike*.

A. The Technical Basis

Most internal combustion engines operate at their best efficiencies at around 70% of their rated capacity. This is the load at which most of the energy content of the fuel is used to do work. Some manufacturers provide their customers with a "performance curve". These curves are usually different for each manufacturer and for each engine model.

Fig. 1 below shows that the engine is most efficient between 75% and 97% of its rated load. In view of this, the controller-dispatcher will try to operate the engine around this zone, depending upon the amount of charge that the batteries already have, and the load required by the shaft. The system provides more charging current and energy when the charge levels of the batteries are low, and the opposite happens when the charge is high.

The strategy is to choose the size of the engine that can be operated around this efficient zone for the kind of road conditions and of load that it will transport. The maximum design load conditions for this first prototype are estimated and assigned at 70% of the required engine rating. The exact loading scheme will be calibrated at a later time, and it will take its cue from the charge level of the batteries and other factors, such as the actual performance curve of the specific engine procured. The software program that resides in controller-dispatcher of the vehicle will start the engine and shift the load to it *at*, or, *near* the full capacity of the motor. If the load on the engine at this point is below the efficient zone, the controller-dispatcher will provide the needed additional shaft load by activating the charging system. During this time, it will balance the engine power, the load required by the shaft, and the load on the generator to provide a relatively smooth ride.

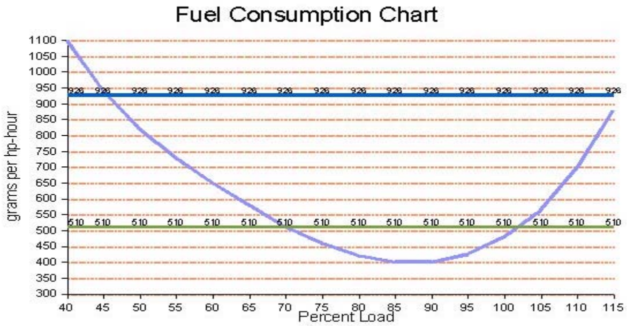

Fig. 1 - A Typical Performance Curve

The rating of the electric motor is chosen to be a relatively large percentage of the capacity of the engine to allow the engine to be in a shut-down state much longer. The ampere-hour capacity of the battery and the electric motor installed on the *A-Trike* set the limit for the ratio of the running time VS the charging time. A higher ampere-hour rating with the same motor would enable the system to deliver a higher charging current to the batteries. The second-hand automotive alternator has enough capacity for the recharging function.

B. Heavy Traffic Conditions

Some of the characteristics of heavy traffic as they relate to the HEV are the following:

- *Idling*. As the automobile's internal combustion engine idles for several minutes, it actually burns fuel very inefficiently making it an obvious environmental hazard. Furthermore, it simply sits on the road consuming gas without any resulting benefit.

- *Low Gear*. When the vehicle starts to move at low gear, its consumption of fuel per mile is high. This consumption is roughly estimated by the amount of pressure that the foot exerts on the accelerator pedal. Pressing on the pedal stronger will get the system to release more fuel into the combustion chamber. The vehicle, though, in this condition, has moved a relatively short distance compared to the distance it would have moved if the same pressure were applied to the accelerator while driving on a highway.

- *Low Engine Load*. While the vehicle is on low gear for prolonged periods, the amount of shaft power that is demanded from a big engine is a small fraction of what the engine is rated for. This shaft demand will be higher, when taken as a percentage of the rating of a small engine. The performance curves of other engines will be similar to the typical curve given in Fig. 1, above. Directionally, there is a corresponding penalty when the shaft demand as a percentage of the rating is small - more fuel consumption per mile. At higher gears, the actual percent load on the engine is increased. Fig. 1 shows an improved fuel economy.

The *A-Trike's* design decreases the amount of time that the engine would run at a low percent load, by leaving most of the traction to the AC motor at these loads. In so doing, this motor must be powered by a source that can provide the higher energy requirement of the system, leading to larger ampere-hour battery ratings to sustain the load. This, in turn, will need a higher charging current from the generator, resulting in a higher shaft input, which in turn, increases the percent load on the engine. This higher percentage load will bring the operation to the higher efficiency section of the curve.

The "*rule of thumb*" imposed upon the *A-Trike* design under this setting of low gear, start/stop, heavy traffic is

> "*if the engine is to be run at all, it should be at, or, near its best efficiency region in the performance curve, and the capacity of the batteries must be considerably large to sustain the larger energy needed by the motor*"

The result is a smaller engine compared to its conventional counterparts, and a battery bank, a motor, and a generator that correspondingly has higher ratings.

The *A-Trike* and other vehicles will be part of a caravan to follow a *path plan*. Before proceeding, a *quality assurance officer* will fill the gas tanks of all the participating vehicles to the brim. He, then, weighs all the vehicles with their passengers. He adds weights on lighter vehicles, so that the physical conditions external to the prime movers are guaranteed to be the same. The caravan will, then, move as planned with the *A-Trike* leading the way with the *quality assurance* officer following at the end of the caravan. At the end of the path, the *quality assurance officer* will fill the respective gas tanks of all the participating vehicles another time. He would then record and compare the gas consumption of each. The caravan approach is significant in that it gives the assurance that all the vehicles will be traveling under the same driving conditions.

Ateneo developed its own simple simulation spreadsheets to predict the ballpark values of efficiencies of a single engine when operated *with* the hybrid component installed, and *without* it. A reduction of 15% or more in the specific fuel consumption (grams per kilowatt-hour) is predicted. An even better result is predicted when compared with existing tricycles, since these have bigger engines than the *A-Trike*.

Simulation software packages [6], [7], [8], [9], [10] offer methodologies that could help test the *A-Trike* design. A serious effort will be made to look at these software packages for possible use in the Ateneo Hybrid-Electric Project, especially as it scales up to the passenger jeepneys and buses that are powered by diesel engines.

C. The Dispatch Curve and Sequence of Actions

The controller-dispatcher will now implement the "*rule*" for the heavy traffic conditions described above. It follows a *Dispatch Chart* as it issues commands to all the equipment within the vehicle to operate at specific conditions.

It translates this chart into a set of actions that will be performed during the operation of the vehicle. This will be discussed in the next paragraphs. The controller-dispatcher interprets the driver's accelerator, clutch and brakes commands so that the vehicle operates in the following manner:

- The VFI frequency is increased, but its output voltage remains close to zero. The output voltage is ramped up to the level allowed by the current limiters, in order to engage the magnetic coupling between the rotor and the rotating magnetic field of the three-phase stator. This action of increasing the strength of the magnetic field effectively decreases the so-called "slip" of the induction motor. The frequency is increased further and the vehicle gains speed.

- The shaft of the engine is engaged with the already rotating shaft of the drive to serve as its starter when the motor load reaches between 600 watts and 1,000 watts, depending upon the charge level of the battery. This action is done manually during its initial runs.

- A small DC motor is converted into a variable-torque actuator. It is given a signal to increase the opening of the throttle to allow more gas into the combustion chamber. The engine starts to share the shaft load with the motor as it increases speed beyond the present operating speed of the motor shaft. The engine will slowly take over from the motor until it carries the entire shaft load at synchronous speed, after which, the motor load will become zero. The operating mechanisms of this prototype will disengage the motor to prevent it from being run as a generator.

- The controller-dispatcher will modify the crossover points of the Dispatch Chart in Fig. 2 as the vehicle progresses. The charging curve "Pch" will have a lower peak and a shorter duration if the charge levels of the batteries are high. The opposite is true when the charge levels are low. Moreover, the motor "Pm" would de-load early with an earlier start of "Pe". The dynamism of the dispatch chart is influenced by the amount of energy consumed from the batteries. A longer running time for the motor will result in a significant decrease in battery charge. This condition shifts the crossover point in dispatch chart to the left.

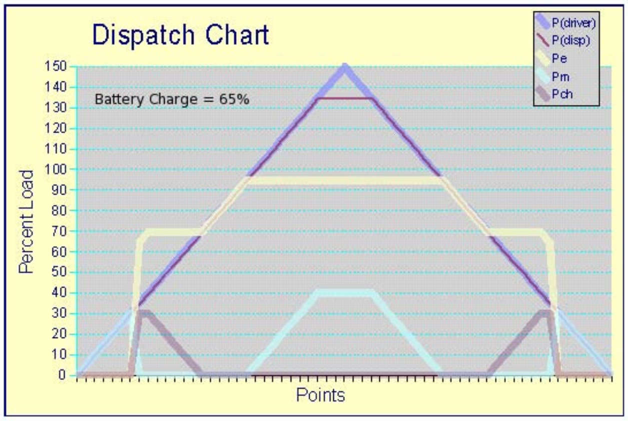

Fig. 2 - The Dispatch Chart

III. THE MAJOR SYSTEMS

This section describes the detailed operation of the three major systems of the HEV: the controller-dispatcher, variable frequency inverter, and the high voltage charger.

A. The Controller-Dispatcher

The controller-dispatcher is a general-purpose equipment that will be used to implement all the functions of the HEV system for vehicles on which it will be installed. It is equipped with input and output ports (I/O) that can accept voltage and/or current from any outside device and provide voltage and/or current to any actuator. The voltage levels for this prototype are 0 to 5 volts, while the current levels are 0 to 20 ma. These will be converted later into the industry standard of 1 to 5 volts and 4 to 20 ma, to make it a truly general-purpose equipment.

Data output to the different channels are *not latched*. The 8-bit output is sent directly to a DAC, whose analog output is sent to a signal conditioning circuit. Analog switches distribute this output to the various channels, which are provided with appropriate capacitors to store the information for the buffers and eventually the actuators. Each of the channels is fast-scanned and the data are stored in capacitors each time, resulting in stable voltages sent to the actuators.

This method radically simplifies the calibration process. There is only one signal conditioner whose *zero* and *span* adjustments are to be manipulated. Other calibration adjustments are done at the software side, where each channel is provided with a multiplier that is applied on the parameter corresponding to that channel.

It also *drastically reduces component count and the associated control circuitry*. The decrease in component count will result in an *increase in reliability*.

In the present set-up the controller-dispatcher resides in a laptop computer, which is provided with dual boot to the command-line MSDOS and command-line LINUX operating systems. The control software is written for both operating systems. Work is underway to migrate the controller-dispatcher function into a stand-alone microcomputer, with the laptop computer serving as a wireless data link to a main database that that is used in efficiency calculations, and in environmental impact studies.

The chart in Fig. 3 shows the path of communication between the modules. This chart is provided to give an overview of how the systems and the working groups interact with each other.

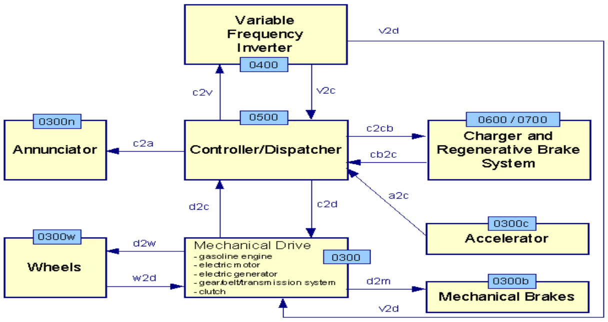

Fig. 3 - Communication Chart Between Modules

B. The 3-phase Sinusoidal Variable Voltage and Variable Frequency Inverter

The VFI takes DC power input from a series-connected battery bank composed of seven 12-volt cells and provides a sinusoidal variable voltage variable frequency three-phase 230-volt WYE output. The WYE output has been chosen so that the line-to-ground voltage does not significantly go beyond 133 volts. This voltage and the battery terminal voltage of 105 volts DC as it is being charged are considered reasonable compromise values for the safety of the passengers.

The variable frequency inverter will be subjected to a *heat run* similar to that conducted for generators installed in power plants. This will be done before proceeding with the exhaustive road tests to gain the assurance that the *VFI* will be able to function within its design working load conditions.

The inverter generates three-phase sine waves in the following manner:

- Encode two half parts of a sine wave in one EEPROM. Call this E(a).
- At a space of 120 degrees, encode another two halves of a sine wave in another EEPROM. Call this E(b). In a shift register, this is like shifting with rotate E(a), so that the portion of this wave that exceeds E(a) will be relocated at the starting point of E(a).
- At a space of 240 degrees from E(a), encode another two halves of a sine wave in another EEPROM. Call this E(c).

This is the same procedure as above.

- Connect the address pins of the three EEPROMs to the output pins of two cascaded binary counters, whose less significant byte takes its clock input from the output of an astable multivibrator.
- Also connect the pins of a programmable logic device to the address pins. This PLD is programmed to provide a logic "1" output for the first half sine wave to control the IGBT switch on one side of the output transformer, and a logic "0" that is inverted to become a logic "1" for the next half. A logic "1" on one side allows that IGBT to be switched, to pull down one side of the transformer in Fig. 4.

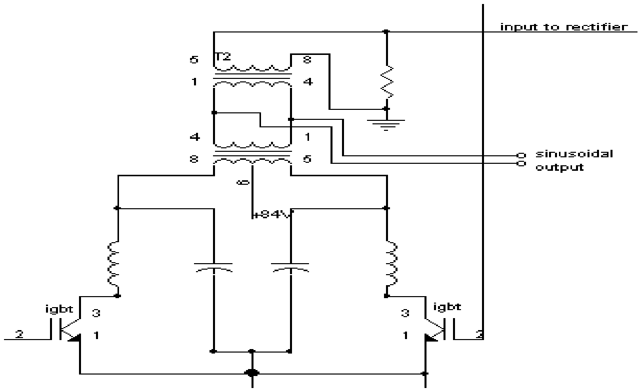

Fig. 4 - Output Section of the VFI (simplified)

- Provide digital to analog converters (DACs) for each of the three EEPROMs and *condition* these half sine waves to become reference signals to three comparators.
- The other inputs to these comparators come from conditioned voltage feedback signals taken from the output of the VFI, Fig. 4 'input to rectifier', and the current sensors.
- The 3-input AND gate in Fig. 5 accepts voltage switching input at pin 3, instantaneous current input at pin 2, and at pin 4, the signal that determines which half section of Fig. 4 is switched. Pin 4 goes to logic "1", and if the voltage is lower than the reference half sine wave AND the current is lower than the dynamic reference, then the IGBT at that side will switch ON until either the voltage OR the current reference signals are surpassed.

A "dynamic reference" signal is provided to all the three phases, such that an abnormally high current in any one phase will generate a signal that will quickly bring down the amplitudes of *all* the *sine wave* reference voltages. The output voltages will also be brought down, since the reference voltages are low. This function is the *safe shutdown* feature of the project. A "line-to-line" or a "line-to-ground" short simply cause a shutdown. The system goes back to normal when the short is removed.

This first prototype model could be provided with an automatic clutch in the *electric mode*. The choice, however, was to give the driver an environment which is very much similar to the clutch he grew up with. Thus, as he manipulates the clutch, the driver effectively controls this dynamic reference. When he operates the accelerator, he controls the frequency, and when he steps on the brakes, he is recovering some kinetic energy and/or difference in potential energy and sending this recovered energy back to the batteries.

Fig. 6 is a combination of waveforms taken from the VFI and are superimposed to form the whole picture. Section "A" is the reference signal coming from the EEPROM and accepted at pin 2 of the LM311. The upper half of section "B" goes to the gate of the IGBT on the left of Fig. 4, and the lower half goes to the gate at the right. Section "C" determines whether it would be the left or the right IGBT that should switch. Section "D" is the sinusoidal output indicated in Fig. 4. The current input is taken from the pilot windings of the inductors at the collectors of the IGBTs. It operates along the same principle as the current transformer.

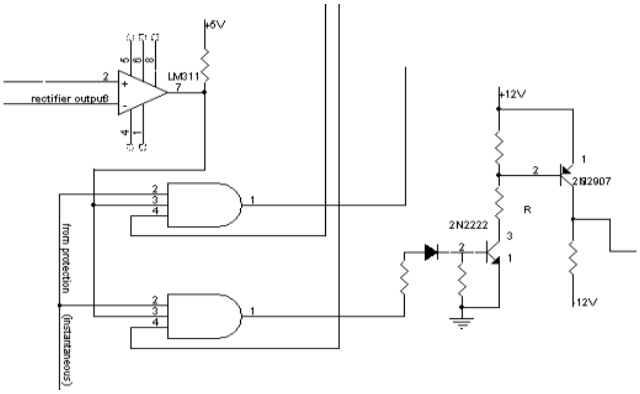

Fig. 5 - Switching Section of the VFI (simplified)

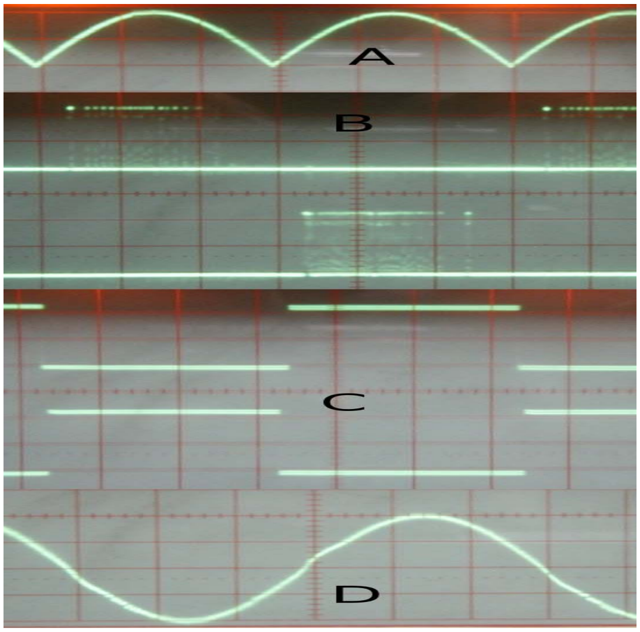

Fig. 6 - Actual VFI Oscilloscope Tracings

C. The Intelligent Battery Charger

The intelligent battery charger manages the charging current so that at no point during the charging process would it allow more current into the batteries than is safe for the current state of the batteries. It looks at the level of charge by taking the terminal voltage of the batteries connected in series, and by its own hardwired system limits this current. The design is guided by the DOE HANDBOOK (DOE-HDBK-1084-95) on lead-acid batteries [11]. Yuasa batteries provide tips that are useful for working with these batteries[12].

The system monitors the terminal voltage of each of the batteries and sends an alarm if any one of them should come close to an overcharged condition. In any case, an IGBT-based switch that is connected in series with an inductor closes, when the limit for the terminal voltage is reached. It regulates the terminal voltage of the battery. In this way, the uneven chemical conditions of the batteries that are connected in series do not become a source of concern.

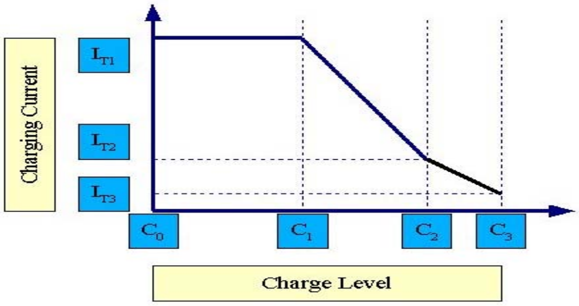

Fig. 7 - Charging Current for Charge Level

Fig. 7 provides a view of the relationship between the level of charge and the charging current. C_0 represents the lead-acid battery's terminal voltage at its minimum charge level. This is around 12.2 volts while charging at about I_{20} up to $I_{2.4}$ (the manufacturer's authorized charging limit) at a cell temperature of about 30 degrees Celsius (note that the numbers given in this discussion are observations in practice and may vary somewhat from one manufacturer to another). C_1 represents float charge at about 13.8 volts, while charging at I_{20}, also depending upon the temperature of the electrolyte. C_2 is the condition at around 75% to 85% charge and one may start observations at about 14.7 volts at a charging current of about I_{50}. C_3 is the terminal voltage when the battery is almost fully charged and observation is usually started at around 15.0 volts at a charging current of I_{100}.

The control algorithm that is used here for the initial *A-Trike* prototype opted for a more conservative approach than is recommended by the DOE [11]. More study and observation is planned to know how the switching operation affects the chemical reactions within the battery. This will be the subject of a further study at the University.

Fig. 8 is a simplified schematic diagram of the system that detects the charge level. It is a straightforward analog sensing, amplification, and diode combination to provide the proper reference signal to the current controller.

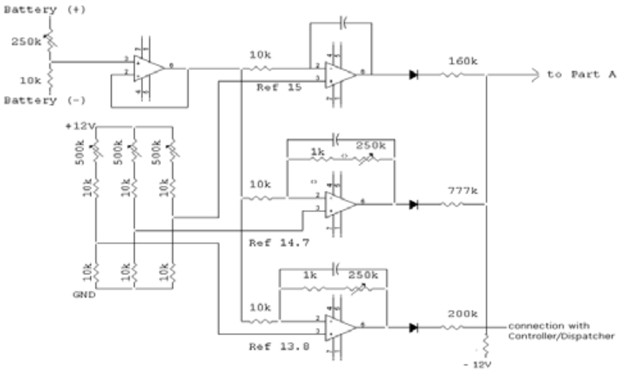

Fig. 8 - Schematic Diagram for Charge Level Detector, the current level controller, and the Controller / Dispatcher / Regenerative Braking System

It is to be noted that all this logic is hardwired and is designed to *override* any and all commands that may increase the charging current beyond the allowable values. These commands may originate from the controller-dispatcher or from the regenerative braking system. Even though hardwired, the system parameters are, nevertheless, monitored by the controller-dispatcher.

Fig. 9 shows the circuit that controls the switching of the IGBT current switch. The inductor that slows down the build-up of current when switched is not shown here.

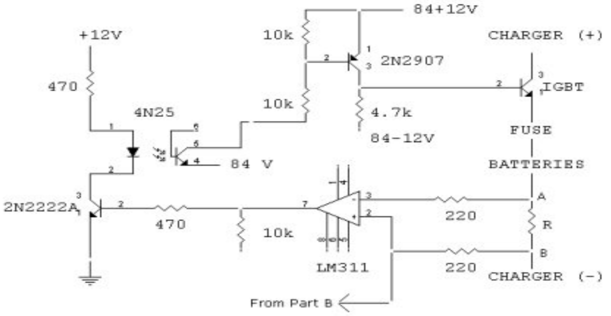

Fig. 9 - Schematic Diagram for Switched Current Controller

IV. CONCLUSION

This project on alternative transport that is designed for Manila may also be applied to other high-density cities. The technology developed here hopes to mitigate the adverse effects of soaring oil prices and carbon concentrations in the atmosphere. The project uses conventional engineering principles applied to the optimization of the overall thermal efficiencies of internal combustion engines installed in vehicles.

Many engine shops in the Philippines assemble second-hand engines and other parts to fabricate passenger jeepneys, buses, and tricycles. A *hybrid-electric black box* would simply be another system that they could readily fasten to the chassis and supports. What may not be immediately evident, though, is that after they have bolted the system and have run it, numerous economic, financial, and health benefits associated with such a system, on a micro level will be realized. On a macro level, the subsequent reduction in fossil fuel consumption will be achieved, thereby protecting the global climate and serving the global community.

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