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Battery Charger using Bicycle

Group B-4

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Abstract

The report discusses the design of a DC-DC converter that can be inserted between the DC generator and the lead-acid battery which is being charged by the generator. The prime mover of the generator is connected to a flywheel which is rotated by the bicycling action. The converter enables charging in a manner which is comfortable for the user, while simultaneously ensuring that the battery is charged in an appropriate manner so as to improve lifetime and performance. We have attempted to design a robust and versatile circuit which meets the above requirements.

1 Problem statement

To design an electronic circuit that can be appended to an existing hardware (a system comprising a bicycle, a DC generator and a lead-acid battery) that will make the charging process more comfortable for the user and increase the life-time of the battery.

Specifications of the generator and the battery we are using:

- DC generator - 10 A, 13 V
  The characterization table and the readings are in the Appendix.

- Lead-acid battery - 80 AH, 12 V

Working voltage and current range of converter:
Input voltage range - 6 V to 16 V
Output voltage range - 10 V to 15 V
Maximum input current - 10 A
Maximum output current - 10 A

2 Introduction

In today's world power is the part and parcel of our lives. It is required for everything - be it the basic necessities like lighting and fans or luxuries like air-conditioners. However, reliable power is not so easily available everywhere. Here we are trying to concentrate to develop an alternative source of power for rural India where power supply is very erratic and unreliable. The basic concept is to store the energy in a battery which can be later used to provide for lighting or can be inverted to run fans etc. A number of viable ways do presently exist to charge a battery. One of them, on which we are going to concentrate, is to charge a battery by pedaling a bicycle. The hardware on which we based our project exists in CTARA, IIT Bombay. The bicycle can be driven by one person or two persons simultaneously. The circuit at present consists of just a diode between the generator and the battery. This is a very crude, though simple way to charge a battery. The user has to bicycle at more than a certain high cutoff speed to start charging the battery as the generator emf must exceed the battery voltage. The torque-speed characteristics are not very comfortable, and remain the same irrespective of whether one or two people are cycling. To overcome the above short-comings, we attempted to design a buck-boost DC-DC converter that can convert any voltage in the input range to any voltage in the output range so that the charging process is completely under our control.

The options we explored initially were:

1. Buck-boost regulator (single inductor, single switch)

2. Flyback converter

3. Forward converter

4. SEPIC converter

We studied each of the above converters, especially the SEPIC and flyback converter, in great detail. We made extensive calculations for the design of the transformer required in flyback regulator. However, the desired current range was causing us to hit the limit of the flyback topology. Finally, we decided to use the highly efficient buck-boost configuration(single inductor, 4 switch) associated with the controller IC LTC3780. This state of the art controller has been released only in early 2006 and can be used to design systems in the 60-100W range having 80% efficiency.

3 Design approach

The hardware constraints, as mentioned in the problem statement, combined with the human constraints(pedaling the bicycle) have been taken into account to come up with a design which can charge the battery over a wide range of emf produced by the generator. The main motivation was to implement the best possible experience for the user. One must note is that a human is not a reliable and continuous source of power. There is a limit to the torque and power can be sustained, which is itself a function of speed. The best possible torque-speed characteristics possible were found from field tests(see Appendix) and the specifications of the converter chosen accordingly. The final system is planned very similar to the exercise cycle in gymnasiums where the user can set a torque value which he finds comfortable(there will be a simple rotating knob for this purpose).

The **hardware** design was planned in three main parts.

1. The power module which consists of an inductor, MOSFET switches and Schottky diodes. Currents of the order of 10A may flow through this sub-circuit. A PCB has been designed and fabricated with thick channels for this module. Large input and output capacitances have been used to reduce voltage ripple.

2. The control module consists primarily of the Buck/Boost regulator LTC3780. It senses the output voltage and current(using a current sense resistor) and generates appropriate gate pulses to produce the required output voltage. This chip is very efficient and provides an excellent alternative to designing and implementing a buck-boost(single switch) or SEPIC converter.

3. The microcontroller module consists of ATmega16 microcontroller, an LCD display (HD162A), a digitally controlled potentiometer(X9421I-2.7) and current and voltage sense sub-modules. Hall sensors are used for sensing the current. The sensors available from the power lab required a dual power supply of 13V, which was not directly available in our system. A DC-DC converter has been incorporated to meet this requirement. The voltage sensing is done

using simple potential dividers. The sensed values(input and output to the power submodule) are fed into the μC using 4 ADC lines. The inbuilt 8-channel,10-bit ADC of the ATmega15 has been used. Depending on the torque set by the user, the μC then varies the digital pot(through the inbuilt SPI interface) which changes the output voltage of the buck/ boost regulator, hence controlling the input current. The LCD display is being used to display the input and output current and voltages. It can also be used to alert the person that the battery is fully charged or he is pedaling too fast and should slow down to protect the generator etc. Thus, the μC performs 3 major functions:

- Sensing the voltage and current at the input and output using the inbuilt ADC. This is the input of the outer feedback loop.
- Controlling the digital potentiometer using the inbuilt SPI (serial peripheral interface). This is the output of the outer feedback loop.
- Displaying the parameters measured and giving the user instructions along with the present state of charge of the battery.

We now move on to the description of the **software**. The μC was coded to continuously obtain the four ADC inputs from current and voltage sensors, to vary the digital pot and to control the display. Using the sensed input voltage and input current, the speed of cycling can be estimated using the parameters of the generator. Now, for an arbitrary torque-speed profile, we know the desired value of input current (since torque is proportional to current). We choose upper and lower acceptable limits for current. If the current is outside these limits, the value of the digital potentiometer is appropriately changed. For example, if too μCh current is being drawn, the potentiometer resistance is increased (it is connected as a rheostat), decreasing the output of the DC-DC converter. This reduces the battery charging current, hence reducing the input current. All this critical operation is done within the interrupt service routine. The driving of the display is done in the main program.

Chosen torque profile - The user can conveniently selected the desired level of torque using a knob. For a given setting of the knob, the charger will switch on at a fixed lower threshold voltage of 6 V, and draw a fixed current (i.e. fixed torque) while the input remains above 5 V. This is as per the data obtained from field tests of 2 cyclists. If the input exceeds 14 V, a warning will flash on the screen, asking the user to slow down in order to protect the generator. The output current never exceeds 10 A because the input current is not allowed to 10 A and output voltage is never substantially below the input voltage. Hence, the battery is always protected from excessively high charging current.

The code will ensure that the currents in the devices do not exceed their ratings and if so shuts off the circuit (by turning off LTC3780), so that no damage is done. It sees to it that the charging process is smoothly initialized and gracefully terminated.

Note how easily the module would be reconfigurable to suit a different kind of hardware, for example a solar powered battery charger or a wind powered charger. In each of these cases, we would know beforehand(or could determine) the optimal V-I profile in drawing power from the input. This would be stored in the μC and could be easily achieved.

4 Design of circuit

The μC ATmega16 was used as it provided a built-in ADC and SPI interface. The buck/ boost regulator LTC3780 was used as it provided us easy control over a wide range of input voltages and high efficiency. Hall probes have been used for current sensing as they are the best (since they reflect a very small resistance in the primary). The number of turns in HALL probe was selected to scale the sensed currents to the required value. The voltage sense resistors are also chosen to obtain data in the desired range (0-5V). The output resistors (15 kΩ and 270 kΩ with a ratio of 18.0) have been chosen to obtain the desired range of output voltage. The value of the inductor was carefully calculated and chosen to obtain a continuous operation over a wide range of currents and hence to reduce the current ripple. The bootstrap capacitor values were also calculated keeping in mind the constraints (that it should be able to store about 100 times the gate charge in the switches). Also devices were chosen so that their power ratings are well above what we will be facing in the functioning of the module. Two MOSFET switches are placed in parallel at each of the four switch-positions to reduce the power dissipation in each of them and as a result reduce the temperature rise.

4.1 Calculations

- Duty cycle of the PWM (in continuous mode of operation of regulator) :
  $D_{Buck-Boost} = (200ns \cdot f) \cdot 100\%$ (where f = 200 kHz, operating frequency of PWM)
  $D_{Max-Buck} = (1 - D_{Buck-boost}) \cdot 100\%$
  $D_{Min-Boost} = (D_{Buck-boost}) \cdot 100\%$

- R_{SENSE} (very small valued resistor used to decide which mode to operate in) selection and Maximum output current
  $I_{out(max,boost)} = \frac{160mV \cdot V_{in}}{R_{SENSE} \cdot V_{out}} - \frac{\Delta I_L}{2}$

$I_{out(max,buck)} = \frac{130mV}{R_{SENSE}} + \frac{\Delta I_L}{2}$

$R_{SENSE} = \frac{2 \cdot 160mV \cdot V_{in}}{2 \cdot I_{out(max,boost)} \cdot V_{out} + \Delta I_{L(BOOST)}}$

- Inductor Selection for the regulator:

  Minimum value of the inductor can be calculated using the following :
  $L_{BOOST} > \frac{V^2_{in(min)} \cdot (V_{out} - V_{in(min)}) \cdot 100}{f \cdot I_{out(max)} \cdot \%ripple \cdot V^2_{out}}$H
  $L_{BUCK} > \frac{V_{out} \cdot (V_{in(max)} - V_{out}) \cdot 100}{f \cdot I_{out(max)} \cdot \%ripple \cdot V_{in(max)}}$H

- C_{in} and C_{out} calculation :

  Voltage ripple and capacitors are related as follows :

  $\Delta V_{BOOST,ESR} = I_{L(max,boost)} \cdot ESR$ where ESR is Effective Series Resistance of the capacitor

  $\Delta V_{BUCK,ESR} = I_{L(max,buck)} \cdot ESR$

  Calculating capacitors at the input and output (depending on voltage ripple)
  $\Delta V_{BOOST} = \frac{I_{out(max)} \cdot (V_{out} - V_{in(min)})}{C_{out} \cdot V_{out} \cdot f} V$
  $\Delta V_{BUCK} = \frac{I_{out(max)} \cdot (V_{in(max)} - V_{out})}{C_{out} \cdot V_{in(max)} \cdot f} V$

- Power MOSFET selection (calculating the switching power losses in various switches) :
  $P_{A,boost} = (\frac{V_{out}}{V_{in}} \cdot I_{out(max)})^2 \cdot \rho_T \cdot R_{DS(on)}$
  $P_{B,buck} = \frac{V_{in} - V_{out}}{V_{in}} \cdot I^2_{out(max)} \cdot \rho_T \cdot R_{DS(on)}$
  $P_{C,boost} = \frac{(V_{out} - V_{in})V_{out}}{V^2_{in}} \cdot I^2_{out(max)} \cdot \rho_T \cdot R_{DS(on)} + k \cdot V^3_{out} \cdot \frac{I_{out(max)}}{V_{in}} \cdot C_{RSS} \cdot f$
  $P_{D,buck} = \frac{V_{in}}{V_{out}} \cdot (\frac{V_{out}}{V_{in}} \cdot I_{out(max)})^2 \cdot \rho_T \cdot R_{DS(on)}$
  $T_J = T_A + P \cdot R_{TH(JA)}$
  In the above equations $\rho_T = 1.5$ and $k = 1.7$. The power dissipation calculations are done taking into account the maximum switching loss for each mode for each switch.

4.2 Numerical Calculations

Constraints and requirements of the design :

f = 200 kHz $V_{in(min)} = 6$ V, $V_{in(max)} = 16$ V

$V_{out} = 10$ V . . . 15 V, $I_{out(max)} = 10$ A

$R_{sense} = 10$ mΩ

ESR (effective series resistance) of capacitors ¡ 100 $m\Omega$

Numerical calculations yielded the following :

$\%\Delta I_L = 40\%$

$L_{boost} > 1.82\mu H$, $L_{buck} > 1.7\mu H$ $I_{out,max-avg(buck)} = 13$ A (due to current limit in LTC3780)

$I_{out,max-avg(boost)} = 16\frac{V_{in}}{V_{out}} - 2$ (16 A due to current limit in LTC3780)

Choosing L = 5 μH, $\Delta I_{L(BOOST)} = 36.25$ %

$\Delta I_{L(BUCK)} = 23$ % (upto 40% ripple is tolerable)

$\Delta V_{ripple} = 0.1$ V :

$C_{out(boost} = 300$ μF, $C_{out(buck} = 90$ μF

Region of application of each mode : $D_{Buck-Boost} = 4\%$

$D_{Max-Buck} = 0.96$ ($V_{in} > 15.1$ V), $D_{Min-Boost} = 0.04$ ($V_{in} < 14$ V)

In between it operates in buck-boost mode.

5 Circuit diagram

The circuits are attached.

6 Tests and results

6.1 Test procedures

The testing of the circuits and the PCBs fabricated was carried out in three parts

1. The microcontroller module was tested first. The μC was programmed to vary the resistance between two terminals of the digitally controlled potentiometer depending on a two bit input given to the μC and the new resistance was displayed on the LCD display unit. The ADC s of the μC were then tested by applying test voltages to the ADC inputs and displaying their values on the LCD display unit. The Hall Probe was also tested and interfaced to the μC by choosing an appropriate number of turns and sense resistor for our expected current rating. The μC was programmed to display the value of the current sensed by the Hall probe on the LCD display unit. We used to microcontroller module to control a DC-DC boost converter using PT5062A and were able to successfully demonstrate the principle of operation by maintaining a constant input current of 400mA ±2% for an input between 7V and 10V, given a load of 160Ω. All these tests were conducted on a bread board. A PCB for this module has been designed and fabricated but needs to be tested.

2. The PCB for the power module was tested by applying continuous gate signals to different pairs of MOSFETs. A current of 2A was passed through the circuit by applying these gate signals to the MOSFET pairs (A,B), (A,C) and (A,D). In each case the voltages at different points of the circuit were measured and potential drops in the PCB channels and across the MOSFETs was measured.

3. The control module cannot be tested independently. After making all the required connections with the power module, the circuit was tested by running the Buck/Boost converter in different modes of operation (CCM,DCM and Burst mode) for varying input voltages. During these tests, instead of using the digital potentiometer to vary the output voltage, a 20kΩ potentiometer was used in it's place.

6.2 Test results

1. The microcontroller module is working on the breadboard. The digital potentiometer could be programmed to change the resistance between two of it's terminals. The ADCs are working and the μC has been programmed with correct scaling factors for the different ADC inputs. The LCD unit is also working. Using a boost converter based on PT5062A, we were able to maintain a constant input current of 400mA $\pm 2\%$ for an input between 7V and 10V, given a load of 160Ω. The PCB has been designed and ordered. It will be ready this week.

2. Tests on the power module showed that the potential drops in the PCB channels for a current of 2A were large (0.02V to .03V). Potential drops across the MOSFETS for the same currents were also of the order of 0.02V to 0.03V. The PCB can thus function at low currents of around 2-3A. however at higher currents, due to large potential drops in the PCB channels, the circuit might malfunction.

3. Tests on the control module showed erratic results. The module was able to control the output and provide the expected output voltage only for a small range of input voltages. The circuit at times also drew currents much larger than expected. Such observations can be attributed to faulty switching of the MOSFETs. When the gate signals were measured we found that they had a frequency of 2MHz as opposed to the 200kHz frequency expected. The signals were also very noisy. The feedback to the control module V_{osense} and the voltage across R_{sense} were found to be noisy and filters were used to reduce noise levels in these signals. However, the circuit continued to function erratically. We believe that the leads for the gate signals are picking up noise and hence it may be necessary to fabricate a new PCB which contains the power module and the control module on the same PCB.

7 Conclusions and suggestions

A fully functional product would have the following features:

- Complete control over speed-torque characteristics as seen by the user. Torque can be maintained at a value set by the user.
- Charging of battery over a wide range of speeds of the generator(300 to 600 rpm).
- Multiple speed-torque profiles programmable for different users/depending on the application.

- Display of the charge state of the battery. Full charge indication. Continuous monitoring of battery voltage.
- Improved battery life due to controlled charging techniques.
- Protection of generator from excessive speed of rotation by providing a warning.
- A high conversion efficiency of above 80%.

We have been successful in implementing the outer control module which would enable us to achieve all these. **We have shown the principle of operation on a lower rating power module using PT5062A boost regulator, where we are able to maintain the input current at a desired value.** The power module and control module PCBs have both been designed and fabricated. As mentioned earlier, they were performing erratically. We intend to solder the duplicate control module PCB with leads of minimal length and test it once more. Simultaneously, we are designing a new combined PCB which we will give for fabrication if the old PCBs do not work.

The converter designed is universal in nature. It can be used for battery charging when the source is unreliable and is not uniform over time, eg. in solar panels or wind power. We only need to change the input $I - V$ curve for charging which can easily be done in software.

When we began the project we wished to come up with a cost-effective solution to the problem at hand. However, we were not able to achieve this due to lack of time and other constraints. Nevertheless, we believe that the cost of our module can be brought to below Rs.1000 if the Hall probe is replaced by some other current sense mechanism.

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8 Acknowledgment

We are grateful to our project supervisors who helped us whenever the need arose. We are also especially thankful to Mr. Dharmraj Ghodke, CAT (Indore), for his generous help and kind support.

9 User's manual

The following would be the main points in the user manual of a completed product:

1. Sit on the bicycle and after settling down switch on the circuit.
2. Use the control knob to set the desired value of torque or resistance felt. A higher torque means a higher rate of charging for the same speed.
3. You may pedal at whatever speed you may want, provided the rated speed of the generator is not exceeded.
4. Follow instructions flashed on the display.
5. Stop pedaling when the display shows that the battery is fully charged.
6. Make sure the battery is not discharged to below 9V when charging is started.

10 Appendix

Hall probe calibration readings are as follows :

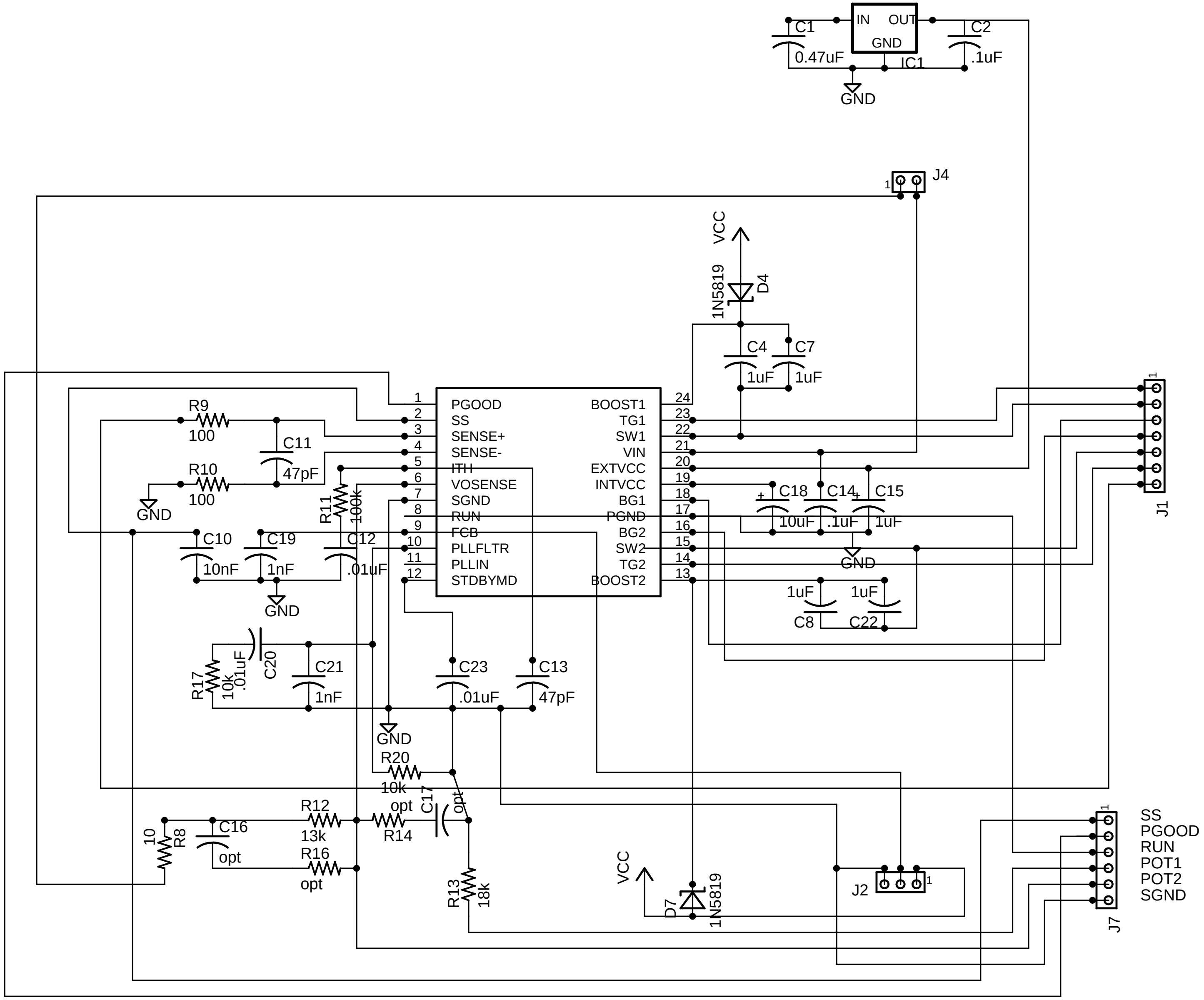
I_{in} (Amperes)	V_o (Volts)
2	0.952
1.8	0.85
1.6	0.757
1.4	0.658
1.2	0.56
1.0	0.469
0.8	0.373
0.6	0.274
0.4	0.178
0.2	0.081
0	0.0

Table 1: Hall probe calibration (for 5 turns)

Voltage-Current profile (data) for the DC-generator (when pedaled by 1 person using a 6 Ω 10 A rheostat (the experiment was done in CTARA) :

V_{gen} (Volts)	I_o (Amperes)
5	8
6	8
7	8
8	7.5
10	5.0
12	4.0
13	3.5
15	3.0

Table 2: Hall probe calibration (for 5 turns)



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PRANSHU ELECTRICALS PVT.LTD.

PERMANENT MAGNET D.C. GENERATOR

TORQUE SPEED CHARACTERISTIC

Generator TYPE:	Gen GD1306		RATED VOLTS:		13.0	Volts
KE:	27.64	V/Krpm	RATED CURRENT:		10.00	Amps
KD:	10.00	Ncm/Krpm	CONT.i/p torque		235	Ncm
			Wattage of Generator		130.00	Watt
TF:	30.00	Ncm	ARM.RES.	RT:	0.24	Ohms
KT:	27.08	Ncm/Amp	RATED SPEED:		600	RPM

T-S CHARACTERISTICS:

I / P Torque in Ncm	AT 15.8 Volts		AT 13.0 Volts		AT 12.0 Volts		AT 6.0 Volts		% OF TORQUE
	SPEED RPM	CT AMPS	SPEED RPM	CT AMPS	SPEED RPM	CT AMPS	SPEED RPM	CT AMPS	
0.0	579	1.32	478	1.28	442	1.27	226	1.19	0.0 %
23.5	587	2.19	486	2.15	450	2.14	234	2.06	10.0 %
47.0	595	3.06	494	3.03	457	3.01	241	2.93	20.0 %
70.5	602	3.93	501	3.90	465	3.88	249	3.80	30.0 %
94.0	610	4.80	509	4.77	472	4.75	256	4.67	40.0 %
117.5	617	5.67	516	5.64	480	5.62	264	5.54	50.0 %
141.0	625	6.54	524	6.51	487	6.49	271	6.41	60.0 %
164.5	632	7.41	531	7.38	495	7.36	279	7.28	70.0 %
188.0	640	8.29	539	8.25	503	8.23	286	8.15	80.0 %
211.5	647	9.16	546	9.12	510	9.11	294	9.03	90.0 %
235.0	655	10.03	554	9.99	518	9.98	301	9.90	100.0 %
246.8	658	10.46	557	10.42	521	10.41	305	10.33	105.0 %
329.0	685	13.51	584	13.47	548	13.46	331	13.38	140.0 %
411.3	711	16.55	610	16.52	574	16.50	357	16.42	175.0 %

Generator should not be loaded for more than rated torque continuously.

DRAWN FOR: CTARA IIT Mumbai on 27-10-2004

BY:.... MPC