APPLICATION NOTE

ICs for Battery Management

Intelligent Battery Packs using SAA1501(T)

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Abstract:

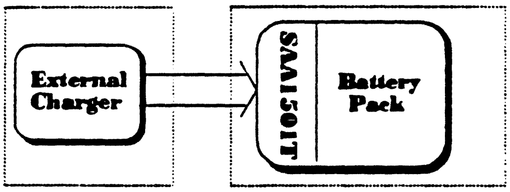
SAA1501T is a low-peripheral battery management circuit to be used in fast charging systems. The most important function of SAA1501T is monitoring the charge account in rechargeable batteries. During battery charging the charge current and charge time are registered in a coulomb counter, whereas during discharging the discharge current and time are recorded. The momentary charge account of the batteries can be displayed either on an LCDisplay or by an LED bargraph.

SAA1501T can be used for three application areas:
1) For intelligent battery pack applications. In order to get an intelligent battery pack, the state-of-charge indicator circuitry is incorporated into the battery pack. Charge control is carried out by the charger which is outside the battery pack (figure 1.a). Typical applications include Camcorder, tools and mobile telecommunications.

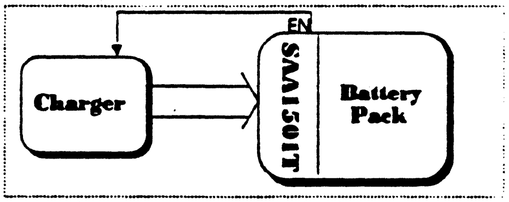
2) For applications with a built-in charger. Then SAA1501T carries out the charge control by means of a current control signal and thus effectively masters the charger unit (figure 1.b).

3) For applications with an external charger which is yet mastered by SAA1501T by means of an additional connection for the current control signal of SAA1501T to the charger unit.

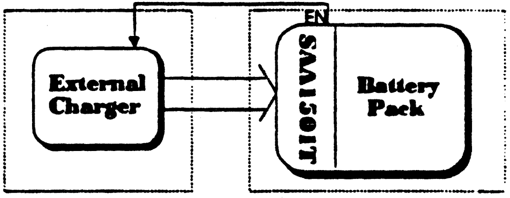
This application note deals with some basic applications for intelligent battery packs only (application area 1). A subsequent application note could be dedicated to the 'charge current regulation' function (application areas 2 and 3).



Intelligent Battery Pack Application
(Figure 1.a)



Application with built-in charger
mastered by SAA1501T
(Figure 1.b)



Application with external charger
mastered by SAA1501T
(Figure 1.c)

Figure 1: possible application areas with SAA1501T.

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1. Introduction to state-of-charge indication

People tend to recharge batteries many times more often than actually necessary, simply because they are afraid of being caught out with empty batteries. This could result in early degradation of battery performance and lifetime. Besides, this can be a waste of time and effort. It can be even worse, when for instance you attempt to record a friend's first band-concert event with your camcorder of which - you think - the batteries are fully charged. However, after having been able to happily record the first part of the performance the battery goes flat just before your friend starts his solo.

Therefore an intelligent battery equipped with a battery state-of-charge-indicator function appears to be indispensible, whereby the function can be regarded as a fuel gauge in a car. The requirements of the indicator are that of an easy to read indication of the available battery energy and a battery low indication prior to when the batteries are really empty.

With SAA1501T we can offer the ideal compromise between prize and flexibility. The SAA1501T uses a highly accurate 'charge-sensing method' and enables charge/discharge efficiency compensation.
The application using SAA1501T only requires a few peripherals.

2. Battery measurement strategies

In order to determine the available battery energy two methods can be considered. Below, these two methods are described together with some elaboration on battery theory.

2.1 Absolute Battery voltage measurement

When considering the battery voltage as a function of charge time of NiCd and NiMH batteries (dashed line in figure 2) it may be concluded that it is possible to use battery voltage measurement to obtain an indication about the status of the battery capacity (state-of-charge indication). However, in case of discharging the batteries, with NiCd and NiMH batteries the flatness of the cell voltage during a single discharge cycle makes the 'absolute battery voltage measurement' method completely inappropriate.
Besides, this method would fail at all because of the dependence of the charge and discharge voltage with temperature, re-charging history and discharge rate.

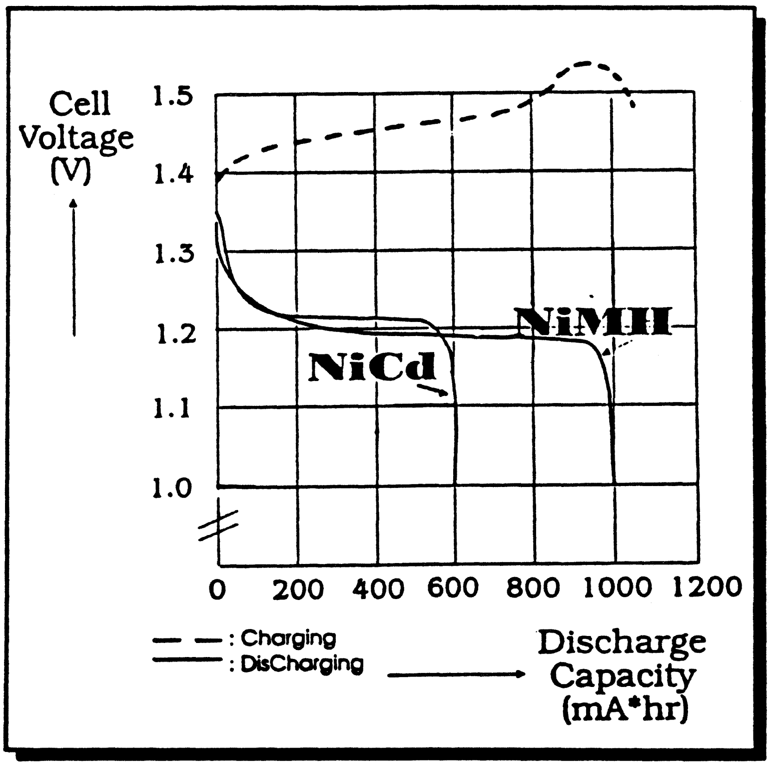


Figure 2: figure of nominal discharge characteristics.

2.2 Charge/discharge current measurement

Measuring the charge and discharge currents together with time gives us an accurate indication of how much energy is in the batteries. However, since the charge acceptance (charge efficiency) and available discharge capacity (discharge efficiency) decreases with charge and discharge rate respectively (there are no batteries with 100% efficiency), some allowance must be incalculated to prevent batteries being empty prior to battery low indication.
Further, some allowance must be incalculated due to battery temperature variation, which also influences charge and discharge efficiency.
SAA1501T uses Charge/DisCharge current measurement and enables charge and discharge efficiency to be set independently.

3. SAA1501T and its key features

3.1 Introduction SAA1501T

SAA1501T is a monolithic integrated circuit designed to provide state-of-charge-indication for rechargeable NiCd and NiMH batteries.

SAA1501T is highly appropriate for use in battery pack applications, as only a few peripherals are required and thus the overall application is extremely compact. A block diagram of a battery pack application using SAA1501T is shown in appendix B.

The circuit is processed in advanced BICMOS technology, wherein the benefits of mixed bipolar and CMOS components are fully utilized and due to this combination high-accuracy is guaranteed.
Since SAA1501T measures charge and discharge currents continuously, hence 'the charge sensing-method' of SAA1501T is suitable for detecting pulsating charge and discharge currents (GSM, camcorders and so on).

3.2 Key features of SAA1501T

- **High-accuracy charge/discharge current measurements.**
- **Large dynamic range of both charge and discharge currents.**
- **Independent settings of charge and discharge efficiency.**
- **Low power dissipation, 90μA quiescent current maximizes battery life.**
- **Few peripherals for easy integration in battery pack.**
- Appropriate for pulsating charge and discharge currents.
- Three charging levels, assuring batteries are fully charged (requires use of charge current regulation signal of SAA1501T (EN-signal) to be connected to the charger unit).
- Temperature-controlled battery self-discharge setting.
- Maximum battery temperature protection via absolute battery temperature measurement (adjustable Tmax).
- Two charge account display modes, six segment LCD or LED.
- LED and audio output for battery empty warning.
- Suitable for all NiMH and NiCd batteries and for each size of battery capacity.
- On-board regulator for controlling an external charger (EN-signal).

4 Functional description SAA1501T

This section explains the functional blocks of SAA1501T. The main system blocks of SAA1501T consist of the supply block, the U/I charge block, the U/I discharge block, the mode recognition block, the temperature block, the U/D Counter block, the display decoder driver block and regulation control block. A block diagram of the IC is shown in appendix C. Refer to the specification data of SAA1501T for the electrical characteristics.

For the terminology of the IC's input and output pins, table 1 can be referred to.

Pinnumber	Pin Name	Desciption
1	Vcc	Supply Voltage
2	EN	Enable
3	Cd	Duty cycle capacitor
4	Ccnt	Charge reservoir capacitor
5	Rmax	Maximum average charge
6	Rref	Current reference resistor
7	Rd	Discharge current conversion resistor
8	Rc	Charge current conversion resistor
9	GNDs	Charge sense input
10	Rsd	Discharge sense input
11	TEMP1	Temperature sensing resistor
12	TEMP2	Temperature setting resistor
13	Co	Oscillator capacitor
14	BUZ	Buzzer (audible BLI)
15	FULL	Full battery indication
16	100	100% segment indication
17	80	80% segment indication
18	60	60% segment indication
19	40	40% segment indication
20	20	20% segment indication
21	BP	LCD back plane drive
22	BLI	Battery Low Indication
23	PO	Power (Charge) On Indication
24	GNDp	Power ground

Table 1: SAA1501T I/Ps and O/Ps

4.1 The supply and bandgap generator block

The supply voltage of SAA1501T ranges from 2V to 5.5V. As the batteries are connected to SAA1501T (Vcc rises from 0 to supply voltage), the digital circuitry is reset (at 1.7V). As SAA1501T monitors 2 cells of the battery pack the system will reset to zero when each cell has a minimum voltage of 0.85V.

The bandgap generator block produces high-accuracy voltages for the oscillator and for the several reference currents which are being used in the U/D Counter block and the Charge current regulation block.

4.2 Charge/Discharge current sensing blocks

The charge and discharge currents are sensed across a sense resistor (Rsense) in series with the battery cells. The resulting sense voltages are applied to U/I convertors, which produce IC-acceptable down-converted charge and discharge currents. Refer to the figure below for the synthesis of the U/I convertors interfaced to the sense resistor.

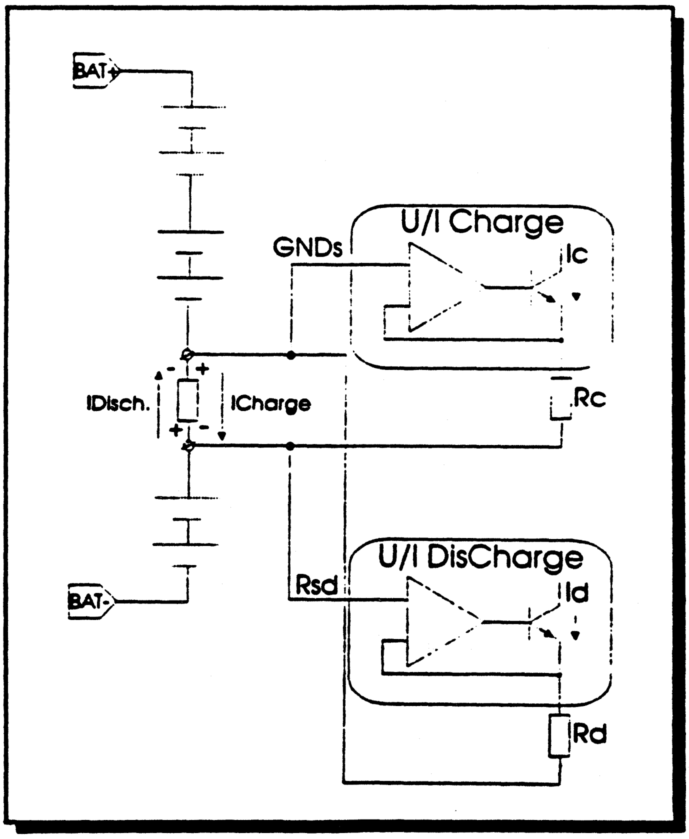


Figure 3: Charge and DisCharge U/I convertors.

4.3 Mode recognition block

For the intelligent battery pack application SAA1501T recognizes three modes of operation, viz. the Charge mode, the Discharge mode and StandBy mode (Self-discharge mode). The mode recognition block differentiates between the available modes of operation.
Refer to appendix D for an operation overview of SAA1501T (flow chart SAA1501T).

4.4 The U/D Counter Block

This block is a true coulomb counting circuit which processes the measured net charge and discharge currents and registrated charge and discharge times representing the available battery energy (Q=I*t). The output drives a two stage counter either up or down depending on whether charging or discharging takes place.

4.4.1 Charge account during the Charge Mode

In case a charge current is sensed across the sense resistor (positive voltage is sensed at input UGNDs) and the batteries are not loaded (no discharge current, so that voltage at Rsd=0V), the SAA1501T will set to Charge Mode. Charge Mode is recognized if the voltage at UGNDs > 3mV, which is called the Idle-level.
The sensed voltage is converted via Rconv to an IC acceptable charge current Iconv. A part of this converted current (1/6*Iconv) will be used for charging an external capacitor Ccnt. A fraction of Iconv is used, so that Ccnt can be small. The voltage on this capacitor will rise until a specified level is exceeded (Ucnt > Uh, refer to specification). On the first rising edge of the internal clock signal a fixed current Iref1 will be distracted from 1/6*Iconv (Icnt) during a defined time N*Tclk, in which N is the number of clock cycles Iref1 is subtracted and thus coulombs are counted. This will result in a voltage decrease at Ccnt in case 1/6*Iconv < Iref1, whereas if Icnt = Iref1, the voltage at Ccnt will not change. During the subtraction of Iref1 coulombs are counted (Q = I*t) during a defined time. Subsequently, after one clock period Iref1 is switched off, so that the voltage at Ccnt increases again, and so on.
Generally, the principle described above is called the 'coulomb counting principle', using a single ADC; refer to figure 4.

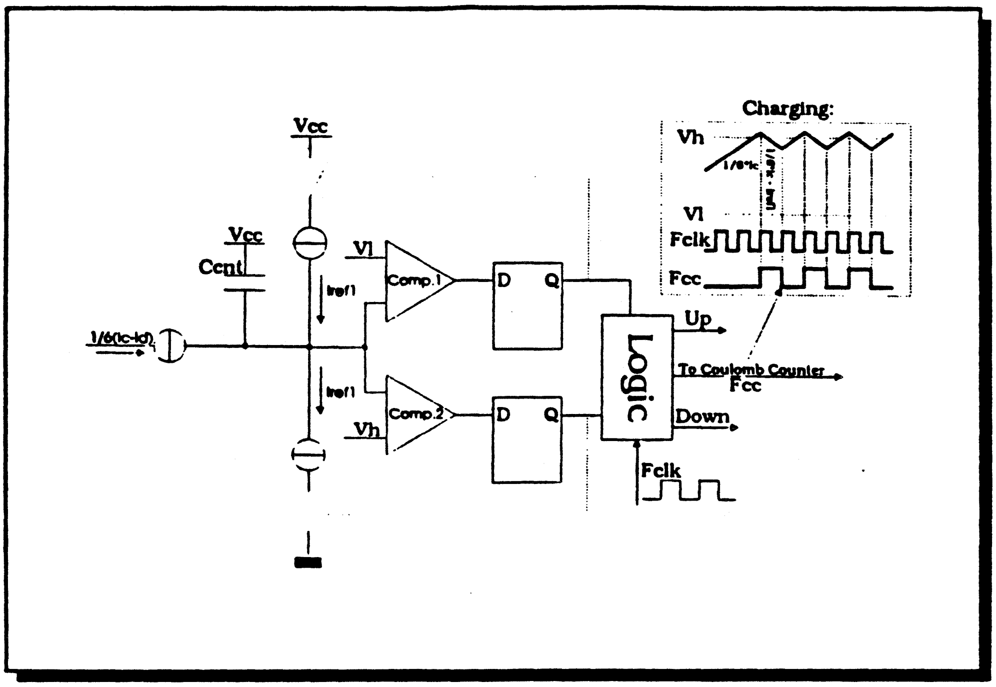


Figure 4: 'Coulomb Counting principle'.

4.4.2 Discharge account during the Discharge Mode

In case a discharge current (batteries are being loaded) is sensed across the sense resistor (positive voltage at Rsd), SAA1501T will set to Discharge Mode (Idle-level to detect discharge mode is also 3mV). The same principle of operation as described in the previous section applies for the Discharge Mode. However, in Discharge Mode Iref1 is added to -1/6Iconv in case Ucnt < Ul (refer to specification).

4.4.3 StandBy Mode

In case neither a charge current nor a discharge current is sensed, SAA1501T is in StandBy Mode. In this mode the counters will countdown in 200 days (Fosc=4kHz) to overcome the Self-discharge of the batteries. In addition, two absolute temperature measurements are carried out in StandBy mode, which enable setting of the countdown rate of the counters as a function of TBattery (refer to section 6.7). This function can be set optionally. The countdown rate is set as a function of TBattery in StandBy mode, otherwise large errors could be introduced.

The quiescent current consumption in StandBy mode is only 90μA. This is a negligible small current compared to the Self-discharge current of the batteries.

4.5 The display functions

With SAA1501T the available battery capacity can be output via six segment LEDs or on a six segment LC Display.

The energy gauge outputs consist of outputs FULL, L100 (100%), L80 (80%), L60 (60%), L40 (40%) and L20 (20%). Further, batteries nearly empty (battery low indication, indicated by flashing LED) and batteries being charged (Charge Mode) are indicated by two additional LEDs, B(attery)L(ow)I(ndication) and P(ower)O(n) respectively. Output BUZZ(er) produces a second battery nearly empty signal which can be used to drive a simple electroacoustic transducer via an external transistor (see figure 5).

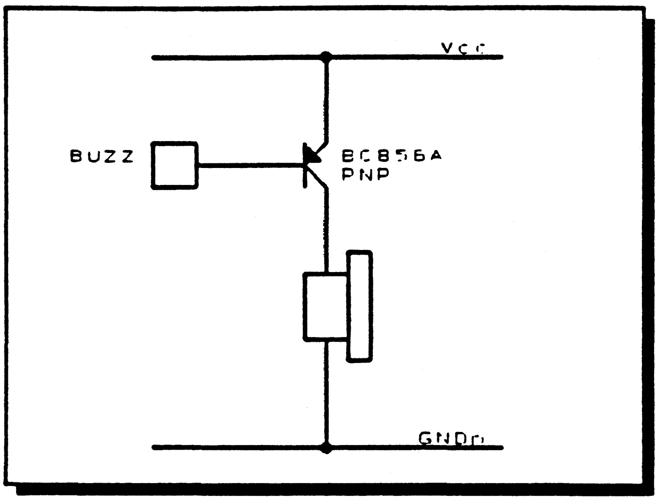


Figure 5: Audible 'Batteries Nearly Empty' Output

The B(ack)P(lane) pin is used to differentiate between LCD and LED modes. LED mode requires that BP is connected to ground, whereas LCD mode requires BP is connected to the backplane of the LCD bar.

In LED mode the energy gauge outputs are made visible by switching on constant current sources (10mA). In LCD mode BP generates a 64Hz block signal and the energy gauge outputs are made visible by producing block signals which are in anti-phase with the signal at BP.

When using LEDs for displaying the available battery capacity the LEDs are only continuously on in the Charge mode, whereas when using an LC Display the display is on in all modes (Charge mode, Discharge mode and StandBy mode). To be able to produce a state-of-charge indication when using LEDs in the StandBy mode, a mode change must be forced manually. In the battery pack application using LEDs this is carried out by pressing S1 (e.g. see appendix E), which thus forces a mode change from the StandBy mode to Discharge mode. Then. the LEDs will be on for 8 seconds.

The values of the voltage dividing resistors R1 and R2 have been chosen so that the input transistors (PNP) of the internal U/I convertors are not completely turned off. Resistor R1 of 10k introduces an offset voltage of 0.1mV only at the Rsd input of the discharge U/I convertor, since the bias currents of the inputs of the U/I convertors are 10nA.

4.6 Charge current regulation

This block produces a charge current regulation signal, to be used for controlling an external current power supply, such as the TEA1400. As this report is specifically meant for Battery Pack applications, the charge current regulation block is not utilized with the battery pack application. A follow-up application note on SAA1501T could be dedicated to applications using charge current regulation, e.g. desktop charger applications.

4.7 The oscillator and prescaler/controller

The oscillator is a relaxation type which drives the prescaler/controller. The prescaler/controller provides all system timings, which all are related to the oscillator frequency (Fosc). When running at a speed of 4kHz (Fosc), the prescaler/controller takes care of derivating signals of 2kHz for the buzzer (BUZZ), 64Hz for the LCD backplane, pulse trains for the temperature block and power sensing measurements, 2Hz signal for dynamic charge/discharge indication, Self-discharge timing-signals, and a signal with a duration of 8 seconds for read-out purpose of the LEDs as was already mentioned in section 4.5.

4.8 Temperature block

This block includes two functions. One function is to terminate fast charging when battery temperature exceeds a certain maximum temperature level. At this temperature TFC (Fast Charge Turnover point) temperature protection is activated which means that the external charger is requested to switch over to slow charging via a current regulation signal of SAA1501T. This is necessary since fast charging at high battery temperature (for instance 60°C) will damage the battery and thus degrade battery life and performance.

The other function is to adjust the Self-discharge countdown of SAA1501T as a function of temperature. This is necessary since the Self-discharge rate of the batteries is temperature dependent, i.e. the Self-discharge rate of the batteries increases with battery temperature.

The actual battery temperature is measured every 16 seconds (Fosc=4kHz) at pins Temp1 and Temp2 by use of an NTC and some setting resistors (all external). The number of resistors used is optional (2 up to 4). The NTC should be connected close to the batteries. During Charging (Charge Mode) one absolute temperature measurement (TFC) is carried out, whereas in StandBy Mode (Self-discharge Mode) two absolute temperature (TSB1 and TSB2) measurements are carried out. These three absolute temperature turnover points (TFC, TSB1 and TSB2) can be set independently.

It should be noted that TFC is not used in the battery pack application, as the charge intelligence is left to the external charger unit.
The StandBy turnover points TSB1 and TSB2 are directly related to TFC. Refer to section 6.7 how to set the three absolute temperature turnover points.

5 Regarding the SAA1501T system accuracies

5.1 Accuracy of battery characteristics

In the application examples given in this report, it is first tried to fit the batteries into a fixed model, at room temperature and nominal (0.1CA) charge/discharge rates. In here, charge and discharge efficiency of the batteries are taken into account by setting 'average efficiency factors'. These factors are determined by regarding the expected temperature operating range and Crate ranges of the batteries. Thus to assure that the batteries are not empty prior to battery low indication, e.g. the discharge efficiency is set to 70%, which means that 70% of the Standard battery capacity is available by indication during discharge (under-estimated indication). It should be noted that the 'efficiency factors' highly depend on the type of battery used.

The main error between the fixed model (above mentioned) and the perfectly compensated model for temperature and charge/discharge rates, determines the accuracy of the indicator.

Even with a perfectly compensated model the accuracy depends on the accuracies of the characteristics from the battery manufacturer. It is known from literature that the best accuracy with which the characteristics of the rechargeable battery can be attained for typical consumer use is about ±5%.

5.2 SAA1501T performance characteristics

The accuracy of the state-of-charge-indicator function of SAA1501T depends on the accuracy of the 'Coulomb counting' principle, i.e. the accuracy of the current conversion during an accurate time. These two 'settings' are defined by the accuracies of the oscillator frequency and the sense resistors together with the U/I convertor and the conversion resistors.

The error factor of the U/I convertor plays the greatest part in the overall accuracy of the 'coulomb counting principle'. SAA1501T features a wide dynamic range, though in order to achieve best accuracy it should be tried to operate SAA1501T at higher sense voltages (100mV and higher). The typical overall accuracy of the 'coulomb counting principle' is < 2%.

As an aside, it should be noted that the accuracy of the 'coulomb counting principle' is independent of the accuracy of the capacitor at Ccnt (charge counting capacitor). However, use of a low leakage capacitor is required.

6. External components selection

6.1 Rref and converted charge/discharge current range

With Rref the value of Iref is defined by 207mV/Rref wherein 207mV is a fixed (bandgap) voltage at Rref (pin 6). From Iref many bias currents are derived for use in most of the blocks in SAA1501T. Therefore the value of Rref cannot be freely chosen.
For maximum accuracy Iref must be chosen between 3.5μA and 8μA.

The sense voltages at the sense inputs GNDs (pin 9) and Rsd (pin 10) are converted to IC-acceptable currents (refer to section 4.3), i.e. during charging a converted current Ic is produced, whereas during discharging a converted current Id is produced.
The operating range of Ic(Id) as a function of Iref can be written as:

$$\frac{6*2.5*Iref}{100}\mu A \ (= \mathit{Idle\ level}) \leq Ic(Id) \leq 6*2.5*Iref\mu A \ [\mathit{DC\ dynamic\ range}=100] \qquad [1]$$

Formula [1]: the allowed DC range of operation for Ic/Id as function of Iref.

Thus for a nominal Iref=4μA (Rref=51kΩ) Ic(Id) should be in the range from 0.6μA to 60μA for best accuracy. In more detail, then Icmin(Idmin)=0.6μA since below 0.6μA StandBy mode (Self-discharge mode) is recognized, whereas then Icmax(Idmax)=60μA since for currents beyond this level the single bit AD convertor will fail (saturate). It should be noted that this applies for DC behaviour only.

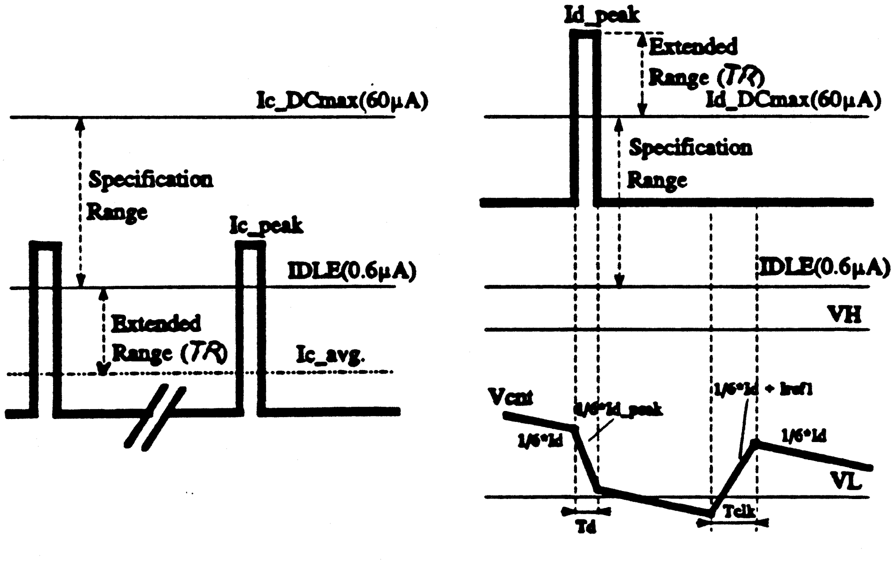


Figure 6: extended current range concerning TR behaviour.

In the previous paragraphs it is said that the dynamic range is a factor 100 (1:100). This applies for DC behaviour only. In case of a pulsated charge/discharge signal (see figure 5) with duty cycle δ and Icpeak(Idpeak) >= 0.6μA (Iref=4μA), the dynamic average charge/discharge range can be raised by $1/\delta$ (the lower range value). Also the upper range value can be raised because of the integration function of capacitor Ccnt. Id_{peak} must ensure that $Td*Id_{peak} <= Iref1*Tclk$ or $\Delta V < (Iref1*Tclk)/Ccnt$; refer to figure 6.
However, the higher the peak currents the more accuracy decreases and therefore it is recommended not to exceed the upper range value by a factor 2 (usually 120μA).
In short it can be said that concerning transient (TR) behaviour the dynamic range can be larger than 1000 times.

Note that the bandgap generator outputs Uref and Umax (pins Rref and Rmax) are sensitive to capacitive load. It is therefore recommended to connect the external resistors Rref and Rmax as close as possible to the IC pins.

6.2 Rsense

Three criteria determine how to choose Rsense:
1) Minimum sense voltage:
The minimum Rsense value must be chosen so that the voltage drop across Rsense does not fall below 4mV: the minimum sense voltage for which accuracy of the U/I convertors is still guaranteed (Rsense_min >= 4mV/Imin_charge(Imin_discharge)). In other words, in case it is tried to design-in for Rsense-values which lead to sense voltages smaller than 4mV at the specified charge/discharge currents, higher Rsense-values should be used.

2) Maximum sense voltage:
The maximum allowable sense voltage is limited by the IC supply (battery) voltage minus 1.6V (Ucc - 1.6V). During charging the supply (battery) voltage will be more than 2.5V with two battery cells. Therefore, sense voltages up to 900mV are feasible without any loss of accuracy.

During discharging however the minimum battery voltage of 2 cells can be as low as 2V. The maximum accuracy is now guaranteed for sense voltages up to 400mV.

3) The choice of Rsense also depends on the power rating ($Psense = Isense^2*Rsense$). It should be observed carefully, that Psense does not become unnecessarilly high.

6.3 The oscillator frequency

The basic intelligent battery pack application using SAA1501T is meant to operate at an internal clock frequency of 62.5Hz (Tclk=Fosc/64), which therefore means that the oscillator frequency at Co must be set to 4kHz (Fosc). Then the counter-synthesis of SAA1501T is able to track charge as well as discharge rates in the range from 0.05C up to 5C, provided that the converted charge currents (Ic) and discharge currents (Id) are in the range from 0.6μA (0.15*Iref) up to 60μA (15*Iref).

The following equation gives an idea on the range of charge and discharge rates as a function of the oscillator frequency:

$$Crate=\frac{Ic(Id)}{12*4*10^3*Tosc},\quad 0.6<=Ic(Id)<=60 \ \ when\ Iref=4\mu A,\ Ic(Id)[\mu A] \qquad [2]$$

Formula [2]: Charge and discharge rates as function of Ic(Id) and Fosc.

Thus in order to be able to track higher charge and discharge rates, the oscillator frequency at Co must be increased by decreasing the capacitor at pin Co. For instance, an oscillator frequency of 40kHz would enable SAA1501T to track for charge and discharge rates from 0.5C to 50C. However, increasing the oscillator frequency will speed up the 100/200days countdown. Therefore some external circuitry is required to switch over to a lower oscillator frequency in StandBy (self-discharge) mode.

	Iref = Vref/Rref = 4μA (Rref = 51kΩ)							
	Fosc = 1/(5.6*Rref*Co)							
Fosc[kHz]	4		8		16		40	
Ic(Id)[μA]	12	60	6	60	6	60	0.6	60
Crate (CA)	1	5	1	10	2	20	0.5	50

Table 2: Ic(Id) values and the corresponding Crates as function of Fosc.

Fosc can also be varied by adjusting Iref, but this is not recommendable because the current swing is restricted to 8μA. Moreover, the TR expansion at the higher range would be zero because of accuracy reason as stated in section 6.2.

6.4 The counting capacitor Ccnt

Since this capacitor receives the down-converted charge and discharge currents, a low leakage type capacitor must be used.

The minimum value of the capacitor is determined by the switching levels Vh and Vl. Within one clock cycle, the voltage at Ccnt is not allowed to fall from Vh to Vl whilst charging, whereas the voltage at Ccnt is not allowed to rise from Vl to Vh whilst discharging. The formula for Ccnt (formula [15]) in the next chapter clarifies.

6.5 The conversion resistors Rc and Rd

By means of the resistors Rc and Rd the charge and discharge currents are converted to IC-acceptable levels. The Rc and Rd resistors are called charge and discharge converting resistors respectively.
The formulae below set out how the actual charge and discharge currents are converted to IC-acceptable current-levels. The Rc and Rd resistors define the charge and discharge rates respectively (refer to section 7.1).

$$Ic = \frac{Icharge * Rs}{Rc}$$

$$Id = \frac{Idischarge * Rs}{Rd} \qquad [3]$$

Formula [3]: conversion of actual charge/discharge currents to IC-acceptable levels.

From literature it is known that both the charge acceptance and the actual capacity of a cell charged at high temperatures are lower than those for a cell charged at room temperatures (23°C), i.e. the cell accepts less charge than that it would accept at room temperatures.
This cell characteristic can introduce an error in the state-of-charge indication. This error cannot be compensated since this would require the "converted" battery capacity in SAA1501T to be adjusted as a function of temperature and this function has not been implemented in SAA1501T, simply because of reasons of space and cost.
External compensation may be possible by using temperature dependent resistors for Rc and Rd so that the rate of the counters in SAA1501T (and thus Crate) is adjusted as a function of temperature. It is highly doubtful whether it is worthwile doing so. As the indication is carried out in rough steps of 20% it is allowed to have some mismatch between SAA1501T and the real battery capacity, provided that the charge/discharge rate ranges and temperature operating ranges stay within the recommended ranges as stated in the battery specification.

In case one is afraid prior mentioned mismatch could become unacceptably large, which then could lead to empty batteries prior to battery low indication, SAA1501T can be designed in so that average charge and discharge efficiency factors can be set independently.

With this effectively under-estimated indication the battery low indication will always take place prior to the batteries are empty.

Pins Rc and Rd are sensitive to capacitive load and it is therefore recommended to connect the external resistors for Rc and Rd as close as possible to pins Rc and Rd. This sensitivity (Cout*Rc(Rd) < 1μsec) is mainly due to the feedback from the outputs of the V/I sensing convertors to inputs Rc and Rd.

6.6 Setting the temperature block

The sections below set out how to set the absolute temperature turnover points. The principle used for the temperature measurement circuit is that of a resistor bridge configuration as shown in figure 7.

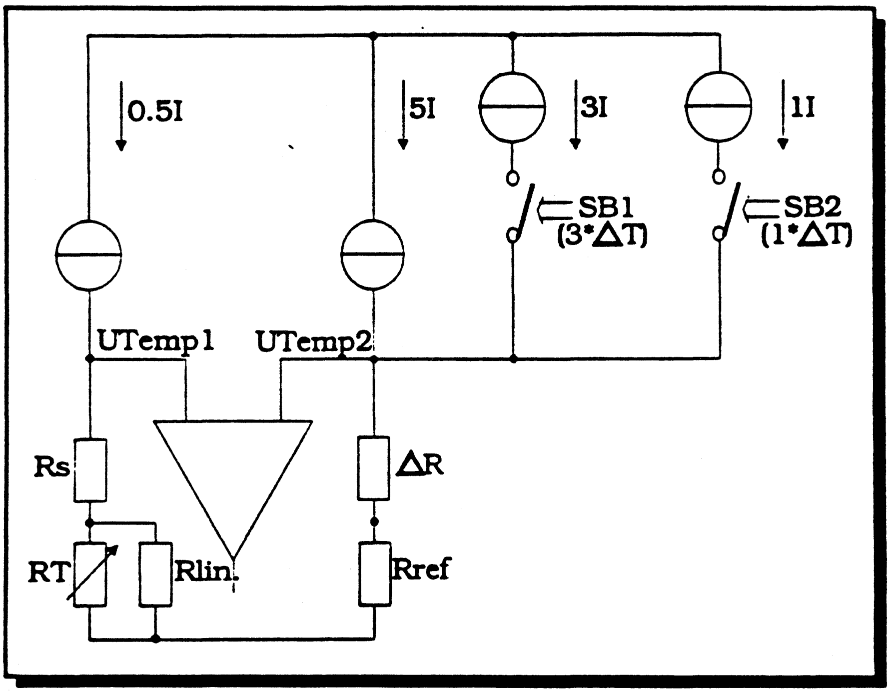


Figure 7: block diagram of temperature block.

6.6.1 Setting the Fast Charge turnover point

As can be seen from figure 7, absolute temperature takes place at UTemp1 = UTemp2 when TBattery = TFC (Fast Charge Turnover point). Then the following equation is valid:

$$0.5I*(Rs+Rp(Tfc))=5I*(Rref+\Delta R),\ so\ that$$

[4]

$$Rp(Tfc)=10*(Rref+\Delta R)-Rs$$

, in which Rp (TFC) = RT(TFC)//Rlin.

In case 0.5I*Rs = 5I*ΔR, Rp(TFC) and thus TFC is only determined by Rref:

$$Rp(Tfc) = 10 * Rref \qquad [5]$$

Now, consider an example in which TFC is set to 60°C. For RT an NTC of type PHILIPS 2322 640 10104 (100kΩ @25°C) is used with characteristic as shown in figure 8. Further, in this example an Rlin. = 100kΩ is used for linearisation of the NTC and Rs and ΔR are chosen so that 0.5I*Rs = 5I*ΔR. Then for Rref a value of 1.87 kΩ (Rp(60°C)) is found (0.1*(100k/23k)).

It should be noted, that a linearisation resistor is only necessary when the NTC curve is not linear in the temperature operation range TSB2 to TFC. Further, the voltage at the Temp1 and Temp2 pins must be between 0 and 900mV.

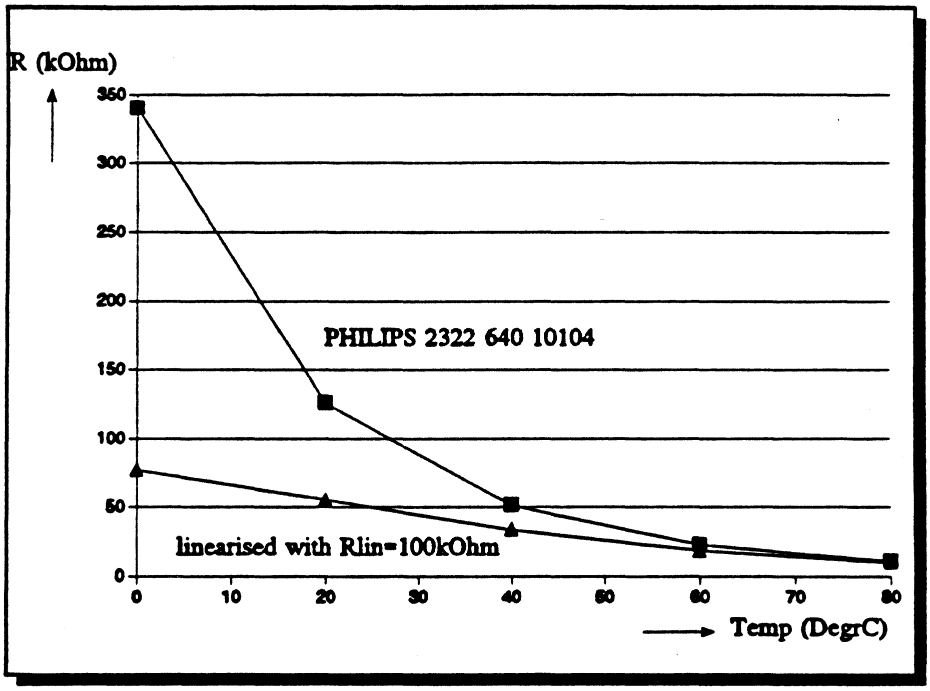


Figure 8: PHILIPS NTC 2322 640 10104 characteristic + linearisation.

6.7.2 Setting the Self-discharge turnover points

As mentioned above two absolute temperature measurements are carried out in StandBy Mode (Self-discharge Mode) and thus SAA1501T differentiates between three temperature ranges. One temperature range is that of battery temperatures beyond TSB1 which corresponds with a countdown rate of 33 days. The second temperature range is that of battery temperatures below TSB2 which corresponds with a countdown rate of 200 days. The remaining temperature range is between TSB1 and TSB2 and corresponds with a countdown rate of 100 days. Figure 9 clarifies.

As can be seen from figure 9, for the absolute temperature turnover points TSB1 and TSB2 can be written as:

$$TSB1 = Tfc - 3\Delta T$$
$$TSB2 = Tfc - 4\Delta T \qquad [6]$$

Further, for ΔT it can be found:

$$\Delta T = \frac{Rp(Tfc) + Rs}{5 * dR/dT} \qquad [7]$$

Now, consider an example in which TSB1 is set to 45°C and TSB2 to 40°C, so that ΔT must be set to 5°C.

Since it was assumed earlier on that 0.5I*Rs = 5I*ΔR, for Rs it can be written:

$$Rs = 5 * \Delta T * \frac{dRp}{dT} - 10 * Rref \qquad [8]$$

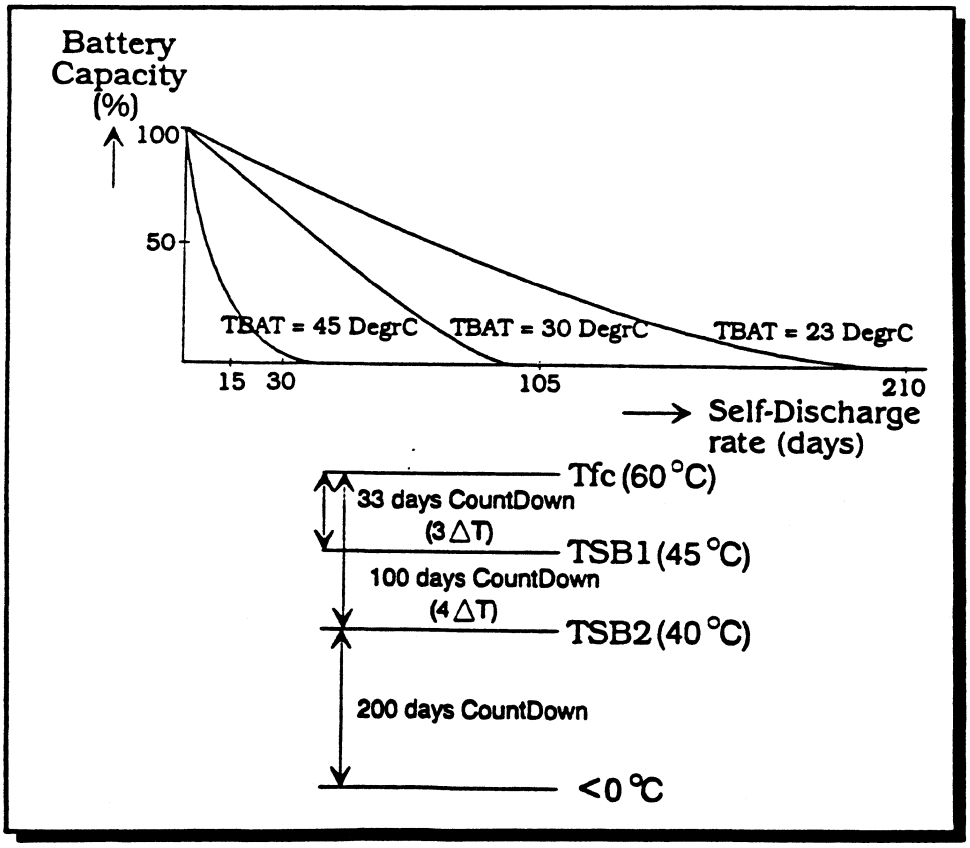


Figure 9: example of a battery with its Self-discharge characteristics as a function of battery temperature and derivation of the Self-discharge turnover points from these characteristics.

The differential value dR/dT follows from:

$$dRp/dT = abs(\frac{R(Tmin)-R(Tmax)}{Tmin-Tmax}) \qquad [9]$$

From figure 8 it follows that in the temperature area 40-60°C the dR/dT=762Ω/°C ((40k2-25k)/20) and thus from formula [5] it follows (using the value for Rref that was found in the previous section) that: Rs = 5*5*762 - 18k87 = 200Ω. Because it was assumed that 0.5I*Rs = 5I*ΔR, ΔR= 2kΩ is found.

In order to assure correct operation of the temperature block, it should be examined whether ΔU > Uoffset(=1.5mV) of the opamp at Templ and Temp2. ΔU is defined by formula:

$$\Delta U=0.5*2E-6*\Delta T*\frac{dRp(T)}{dT} \qquad [10]$$

In this example ΔU = 0.5*2E-6*5*762 = 3.81mV, which is well above 1.5mV.

7 Design-in examples

In this chapter first a general design-in strategy is given for the basic intelligent battery pack application.
Subsequently, an application example is set out by using this design-in strategy.
Further, an exceptional application example will be set out, which requires a non-standard design-in strategy.
In both applications only one sense resistor (Rs) is applied and Iref=4μA (Rref=51kΩ).

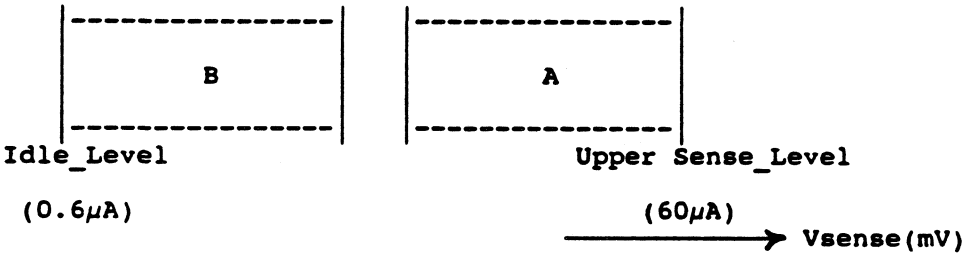
7.1 Design-in strategy for basic SCI application

Restrictions: Rref=51kOhm (Iref=4μA). It should be noted that the value of Iref will not affect the setting of the battery capacity.

1) Determine application charge and discharge rate ranges (in CA) by ICharge(IDischarge)/QBAT, in which QBAT is the Standard capacity value.

2) Examine whether the application Charge and Discharge ranges are within 0.05-5CA. If so, the oscillator frequency (Fosc) can operate at 4kHz (nominal frequency). Use formula [2].

3) Choose Rsense.
Refer to section 6.2 which requirements Rsense needs to satisfy. Further, ideally Rsense should be chosen so that the sense voltages are as high as possible as the relative accuracy of the U/I converters at high sense voltages is better than at low sense voltages.
Thus for the graph below it can be said, that it is best to have the U/I-converters operate in area A.



4) Make sure VIdle>4mV:
The current Idle-level is internally fixed to 0.6μA. This does not apply for the Idle sense voltage, as this depends on:

$$0.6\mu A = \frac{Rsense*ICharge\ (IDischarge)}{Rc(Rd)}$$

However, because accuracy of the U/I converters is guaranteed in the range from 4mV to 400mV, VIdle must be larger than 4mV.

Therefore from the afore mentioned formula it follows that Rc,Rd and Rsense must have minimum values so that VIdle>4mV.
Rsense_min follows from:
Rsense_min = 4mV/Iin_min, in which Iin_min = ICharge_min, if ICharge_min < IDisCharge_min; else Iin_min = IDisCharge_min, if IDisCharge_min < ICharge_min.
Rc_min and Rd_min (=4mV/0.6μA) do not have to be checked as this is implicitly accounted for in the formulae for determination of the values for Rc and Rd ([11] and [12]).

5) Determine values for the charge and discharge conversion resistors. Use the formulae as stated in [11]. These formulae do not take into account charge and discharge efficiency factors of the batteries.
To set average Charge and DisCharge efficiency factors the formulae in [12] should be used.

6) Choose value for reservoir capacitor Ccnt (Coulomb counting capacitor) using formula [13].

7.2 Camcorder battery pack

The application:
- 5 cells, 6Vnominal, 1.2A*hr batteries (Standard Capacity).
- Charge current range: 0.2A to 2.5A (0.167CA to 2.08CA).
- Discharge current range: 0.1A to 3.3A (0.083CA to 2.75CA).
- The application uses only one sense resistor.

1) First examine whether the operational charge and discharge current rates of the batteries are within 0.05CA and 5CA. If so, SAA1501T can operate at its nominal frequency of 4kHz. The charge and discharge rates are defined by: Ccharge_rate = Icharge/{Standard Capacity} and Cdischarge_rate = Idischarge/{Standard Capacity} respectively.
Thus, a maximum charge rate of 2.5/1.2 (Icharge_max/QBAT) = 2.08CA and a maximum discharge rate of 3.3/1.2 = 2.75CA are found here. Further, a minimum charge rate of 0.167CA and a minimum discharge rate of 0.083CA are found. The given charge/discharge current rates are within range. This means that Fosc can easily operate at 4kHz.

   Co follows from the equation:

$$Co=\frac{1}{5.6*Rref*Fosc} \qquad [12]$$

Formula [12]: Co as a function of Fosc.

   In this application example for Co a value of 820pF is found (Rref=51kΩ as Iref must be 4μA).

2) Further, it should be examined whether the sense voltages across Rsense stay within range of the U/I convertors. Preferrably in the range of 4mV up to 400mV.

   Regarding the specified charge current range, with a sense resistor of 20mΩ charge voltages of 4mV (20mΩ*0.2A) up to 50mV (20mΩ*2.5A) will be introduced at the inputs of the charge U/I convertor, which is just within range of the U/I converter. However, for the specified discharge current range, a sense resistor of 20mΩ will give discharge voltages of 2mV (20mΩ*0.1A) to 66mV (20mΩ*3.3A), which is not within range of the U/I convertor. The minimum Rsense value that must be used is 4mV/0.1A = 40mΩ. We choose for a commercially available resistor value of Rs=50mΩ, so that we find charge voltages in the range of 10mV-125mV and discharge voltages of 5mV-165mV, which is satisfactory.
It should be noted that Rs may not be larger than 120mΩ, otherwise the allowed upper discharge voltage is exceeded (120mΩ*3.3A = 400mV).

   For an Rsense=50mΩ a maximum dissipation in Rsense of $P_{Rsense} = (3.3)^2*50E-3 = 0.5W$ is found.

3) The values for the charge and discharge converting resistors are found using the following formulae:

$$Rc = \frac{QBAT*Rs}{12*10^{-6}*4*10^{3}*Tosc} \quad , with\ Fosc[Hz]$$

$$Rd = \frac{QBAT*Rs}{12*10^{-6}*4*10^{3}*Tosc} \qquad [13]$$

,in which QBAT is the Standard Battery Capacity value.

As stated before, to prevent batteries being empty prior to battery low indication, we need to design-in so that SAA1501T operates under-estimated. Then, the charge and discharge efficiency of the batteries are taken into account by setting 'average efficiency factors'. These factors are determined by regarding the expected temperature operating range and Crate ranges of the batteries. From several battery characteristics of Actual Battery Capacity as a function of temperature and Crate, it is concluded that the 'worst case efficiency factor' is 70% when regarding a temperature range of 0-80°C and a Crate range up to 3CA. It should be noted that this factor is highly dependent on the battery type being used.

The afore given formulae for Rc and Rd do not take the charge and discharge efficiency into account. To take these into account the following formulae should be used:

$$Rc = \frac{QBAT * Rs}{12*10^{-6}*4*10^{3}*Tosc*(Charge\ efficiency)}$$

$$Rd = \frac{QBAT * Rs * Discharge\ efficiency}{12*10^{-6}*4*10^{3}*Tosc} \qquad [12]$$

In this basic application it is assumed that it takes 1.43 (charge efficiency 70%) times longer to fully charge the batteries; refer to table 3 for the underlying thought.
Thus for charge rates of 1CA it takes 86 minutes to charge the batteries from empty to full instead of 60 minutes nominally. The value of Rc = (1.2*50E-3)/(12E-6*0.7) = 7k2Ω.

Temp (DegrC) Crate (CA)	-20	0	20	40	60
C/10	70	90	100	102	105
C	50	65	80	82	95
3C	39	56	65	70	78
5C	30	43	58	65	70

Table 3: Actual battery capacity as a function of temperature and Crate.

In the basic application it is assumed for discharging that it will take 0.7 times (discharge efficiency 70%) shorter to discharge from full to empty. Thus for discharge rates of 1CA it takes 42 minutes to discharge batteries from full to empty instead of 60 minutes nominally. Therefore for Rd a value of Rd = (1.2*50E-3)/(12E-6*(1/0.7) = 3.5kΩ is found.

4) The minimum value for Ccnt follows from:

$$Ccnt > \frac{Irefl * 64 * Tosc}{0.66 * (Vh - Vl)} > \frac{10 * 10^{-6} * 64 * Tosc}{0.66 * 0.4}, \quad with\ Tosc[Sec] \qquad [15]$$

,in which it is preferrable to set Irefl to 10μA (2.5*Iref), as stated in the Rref section. In this application example for Ccnt a value of 0.68μF is found.

To avoid continuous switching of the signal at pin CNT between Vh and Vl, Vh-Vl must be larger than ΔVmax = (Irefl*Tclk)/Ccnt. This is the case in this example: Vh-Vl=0.4V and ΔVmax = 0.24V.

7.3 A tools application

The application (an electrical drill-machine):
- 6 batteries, 9Vnominal, 2A*hr batteries (Standard Capacity).
- Charge current range: 0.1A - 14A (0.05CA to 7CA).
- Discharge current range: 1A - 100A (2CA to 50CA).
- Sense resistor: 5mΩ.
- The application uses only one sense resistor.

In the sections below two application-solutions are given. The first one enables SAA1501T to track the full charge/discharge ranges as given above. However, use of some additional circuitry is required. The second application-solution does not require any additional components, however the full discharge range can only be sensed accurately up to 20CA.

7.3.1 Full range solution

1) Usually, tools applications feature wide discharge currents as can be seen in this example. The current values specified here are mean current values. It is therefore feasible, that with a mean charge current of 0.1A a pulsated charge current with $\delta = 10\%$ is sensed across the sense resistor (UGNDs=5mV during the on-time of the pulsated charge signal). And thus we are able to sense charge currents within a dynamic range of 1:140.

   In this example we need to be able to track discharge rates up to 50CA (maximum discharge rate) and minimum charge rates of 0.5CA ($Ic_{peak} = 1A$), thus from formula [2] it is found that Fosc must run at 40kHz. From formula [12] it follows that Co=82pF.

2) Regarding the specified charge and discharge current ranges with an Rs=5mΩ, charge sense voltages of 5mV up to 70mV are introduced, whereas discharge sense voltages of 5mV up to 500mV are introduced. A discharge sense voltage of 500mV is out of range for Vsupply < 2.1V. However, it is feasible that this voltage occurs during circuit-shorts of the motor of the machine for short time, so that the inaccuracy being introduced during this short interval may be neglected.

   For an Rsense=5mΩ a maximum dissipation in Rsense of $P_{Rsense} = (100)^2 * 5E\text{-}3 = 50W$ is found, and thus use of a power resistor is required.

3) From formula [14] it is found that Rc = (2.0*5E-3)/(1.2E-6*0.7) = 11k9Ω (assumed is that the charge acceptance is 70%, refer to previous section).
   For Rd it is found that Rd = (2.0*5E-3*0.7)/(1.2E-6) = 5K8Ω (assumed is that the discharge efficiency is 70%, refer to previous section).

4) From formula [15] a value of 68nF for Ccnt is found.
   To avoid continuous switching of the signal at CNT between Vh and Vl, Vh - Vl must be larger than ΔVmax = (Iref1*Tclk)/Ccnt. This is the case in this example: Vh-Vl=0.4V and ΔVmax = 0.24V (Tclk = 1.6ms).

5) Since the countdown rate in self-discharge mode (SB mode) directly depends on the Fosc (2^{36} * Tosc), which thus means that with tenfold Fosc the countdown rate in Self-discharge mode is also tenfold (20/10 days instead of 200/100 days).
   In appendix F this problem has been solved by means of the circuitry among the opamps LM393A. In Standby mode this circuitry switches on C3, so that in this mode the countdown rate runs at its nominal speed of 62.5Hz (Fosc ~4kHz).

   Refer to appendix F for circuit diagram.

7.3.2 The straight-forward solution

In case it is satisfactory to have a concept which is not able to track for charge/discharge rates higher than 20CA with high accuracy, Fosc can run at lower frequency. Now, Fosc should run at a frequency so that it does not differ much from the nominal frequency (4kHz). As long as the countdown rate in self-discharge is kept above 50 days (nominally 200/100 days) the oscillator frequency does not have to be decreased in the Self-discharge mode.

1) In this example we choose for Fosc=16kHz which is still guaranteed by specification, so that the count-down rate is 50 days in the self-discharge mode.

   For Co a value of 180pF is found.

2) Refer to 7.2.1.

3) For Rc we find Rc = (2.0*5E-3)/(12E-6*0.25*0.7) = 4k8Ω (assumed is that the charge acceptance is 70%, refer to previous section).
   For Rd it is found that Rd = (2.0*5E-3*0.7)/(12E-6*0.25) = 2k3Ω (assumed is that the discharge efficiency is 70%, refer to previous section), whereby we realise that the discharge currents higher than 40A are taken into account as 20CA (maximum charge/discharge rate when Fosc runs at 16kHz).

4) From formula [15] a value of 220nF is found for Ccnt.

   To avoid continuous switching of the signal at CNT between Vh and Vl, Vh - Vl must be larger than ΔVmax = (Iref1*Tclk)/Ccnt. This is the case in this example: Vh-Vl=0.4V and ΔVmax = 0.24V (Tclk = 4ms).

5) With Fosc=16kHz the countdown rate in the Self-discharge mode is 50days.

   This concept does not require any additional components for correcting the oscillator frequency in the Self-discharge mode. However, it is not able to track the full discharge current range accurately; beyond 40A (20CA) additional inaccuracy is introduced.

   Appendix G shows the circuit diagram.

7.4 Typical design-in examples

The table below summarises some typical battery pack applications and their parameters and how to design-in the external components. As in the previous sections, it is assumed that the charge and discharge efficiency is 70%. In the following table this is accounted for in the calculations for Rc and Rd.

Application	Rsense (mΩ)	Batt. Cap. (mA*h)	Charge Curr. (A)	Disch. Curr. (A)	Fosc. (kHz)	Co (pF)	Ccnt (F)	Possible DC Ch./Disch. Rate Range (CA)	Rc (kΩ)	Actual Ch.Rate Range	Rd (kΩ)	Actual Disch. Rate Range (CA)
NoteBook (Colour Screen)	50	2300	1.2	0.8-1	4	820	0.68μ	0.05-5	13k7	0.366	6k7	0.497-0.62
NoteBook (Mono Screen)	50	2300	1.2	0.6-0.8	4	820	0.68μ	0.05-5	13k7	0.522	6k7	0.373 - 0.497
Camcorder	50	1200	0.2 - 2.5	0.1 - 3.3	4	820	0.68μ	0.05-5	7k2	0.116 - 1.45	3k5	0.12 - 3.92
Camcorder	50	2400	0.2 - 2.5	0.1 - 3.3	4	820	0.68μ	0.05-5	14k3	0.059 - 0.73	7k	0.060-1.96
Power tool	5	2000	1 - 14	1 - 70	40	68	68n	0.5-50	11k9	0.35 - 4.9	5k9	0.706 - 49.44
Battery Packs For Cellular telephone	100	1400	1.4	0.7 - 2	4	820	0.68μ	0.05-5	16k7	0.7	8k2	0.71 - 2.0

Table 4: typical SAA1501T application examples.

8 Application possibilities

In the first instance, SAA1501T has been designed for portable applications where battery energy indication is critical. Such applications include:

- Laptop, notebook, and handheld computers.
- Electronic organizers.
- Shavers.
- Camcorders.
- Cellular phones.
- Portable hand tools.
- Portable mobile radio.
- Portable instrumentation such as telecommunications, medical, and analytical.

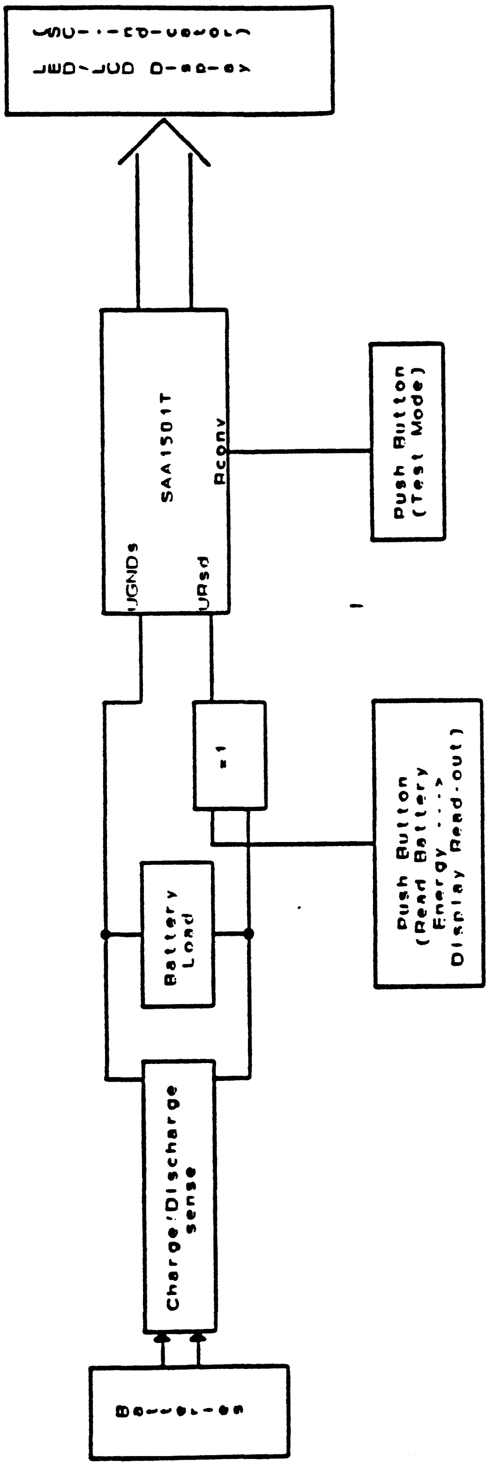
APPENDIX A

Glossary of Abbreviations and Terms

- Actual cell capacity	Measures the total cell capacity under all non-standard conditions that alter the amount of capacity which the fully charged cell is capable of delivering when full discharged.
- BICMOS	Combined Bipolar and Metal Oxide Semiconductor technology.
- BLI	Battery Low Indication output; for visible battery low indication.
- BP	Backplane pin; to differentiate between LED and LCD modes.
- BUZZ	Buzzer output; for audible battery low indication.
- CMOS	Complementary Metal Oxide Semiconductor technology.
- IC	Integrated Circuit.
- LCD	Liquid Crystal Display.
- LED	Light Emitting Diode.
- PO	Power On output.
- NiCd	Nickel Cadmium Battery.
- NiMH	Nickel Metal Hydride Battery.
- SB mode	StandBy mode; in this mode SAA1501T monitors the Self-discharge of the batteries.
- SCI	State-Of-Charge Indicator.
- TFC	Fast charge turnover point.
- TSB	StandBy turnover point.
- Standard cell capacity	Measures the total capacity that a relatively new production cell can store and discharge under a defined standard set of application conditions.

Appendix B

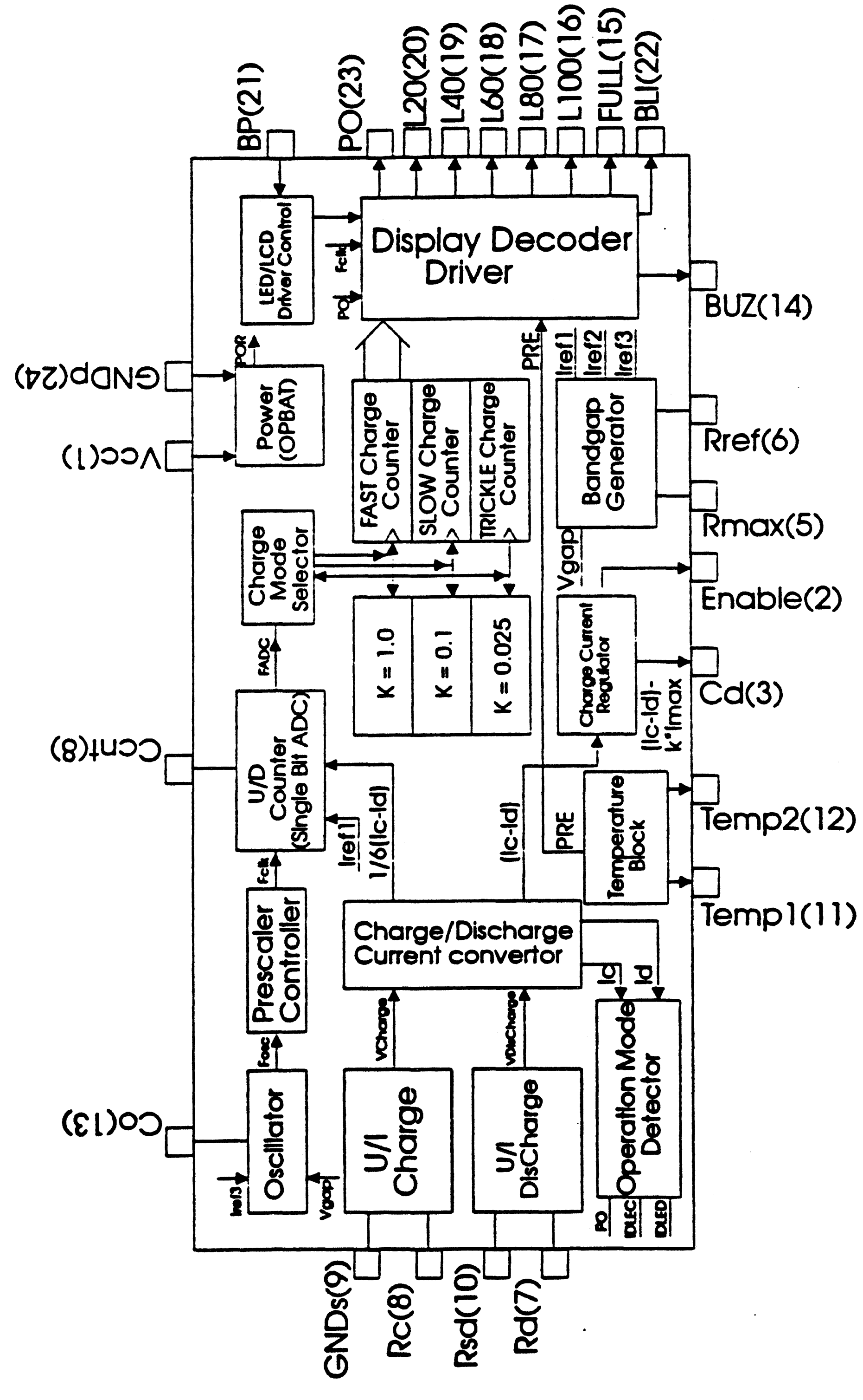
Block diagram of a battery pack application using SAA1501T



Intelligent Battery Pack Block Diagram
(State of Charge Indicator (SCI))

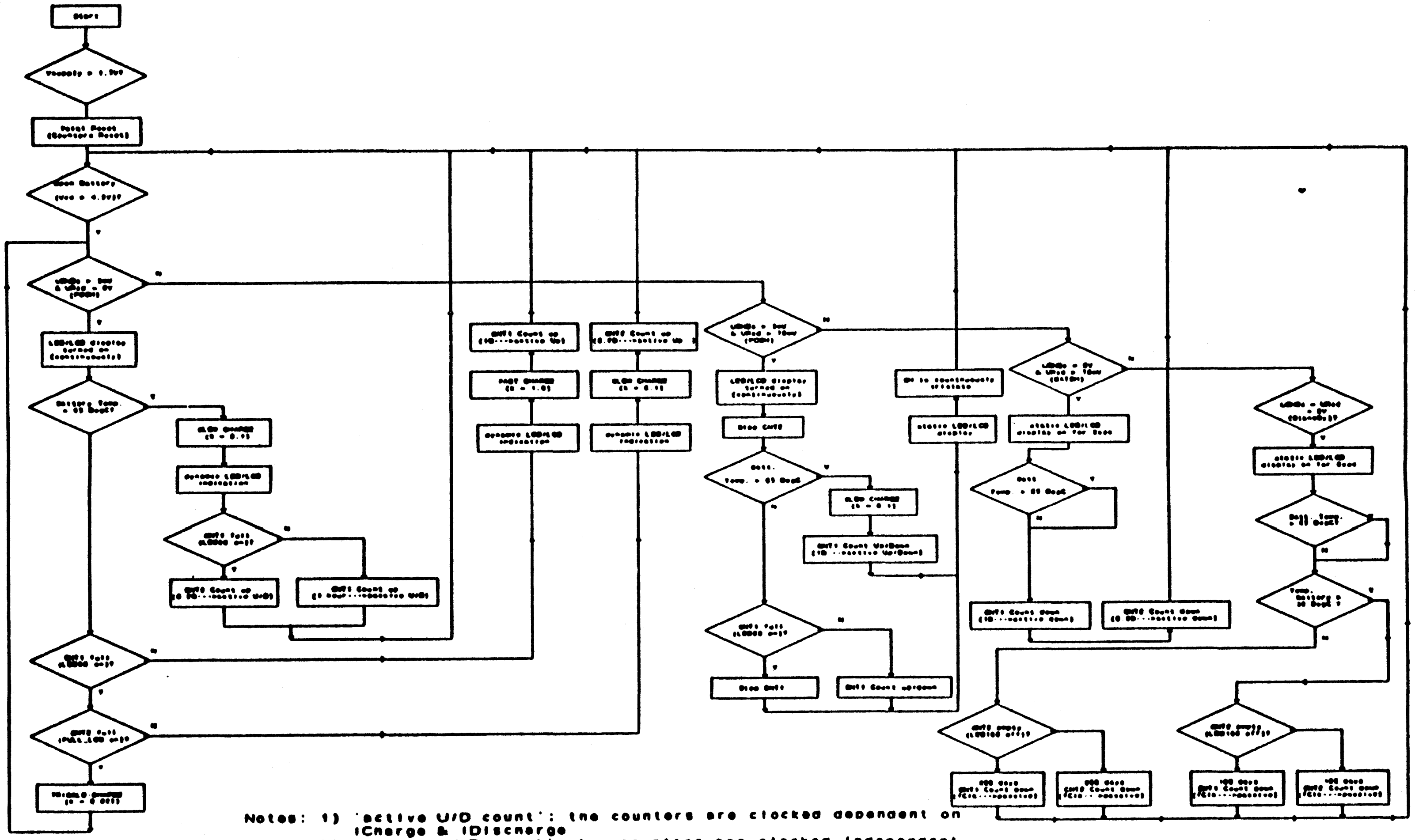
Appendix C

Block diagram of SAA1501T



Appendix D

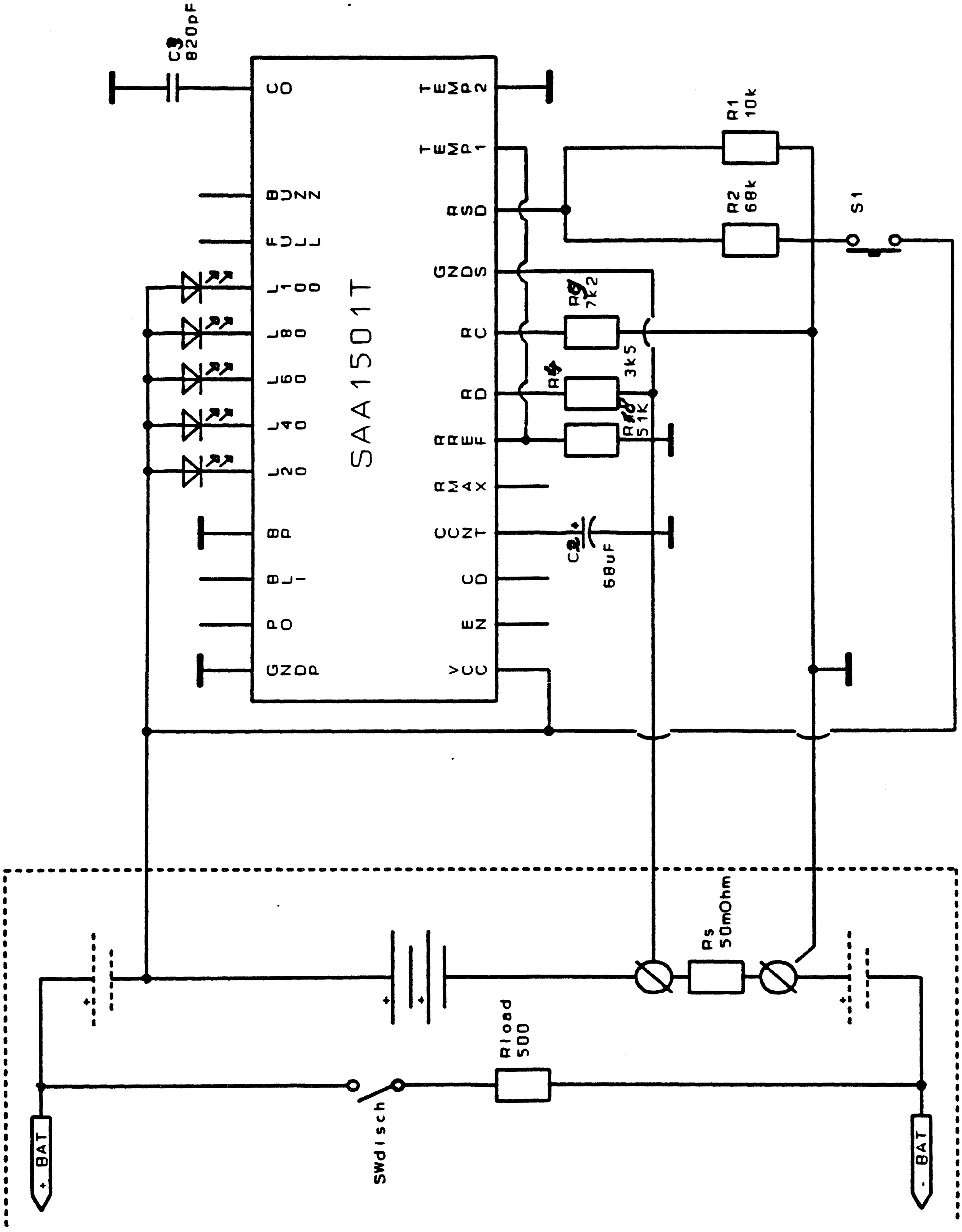
Flow chart of SAA1501T



Notes:
1) 'active U/D count': the counters are clocked dependent on ICharge & IDischarge
2) 'passive U/D count': the counters are clocked independent of ICharge & IDischarge (directly clocked by fClk)
3) 'dynamic charge': LEDs/LCDs are being read-out while current charge-segment LED/LCD is flashing
4) 'static charge': LEDs/LCDs are continuously on
5) this flow chart must not be regarded as sequential. Each operation mode is a separate continuous process.

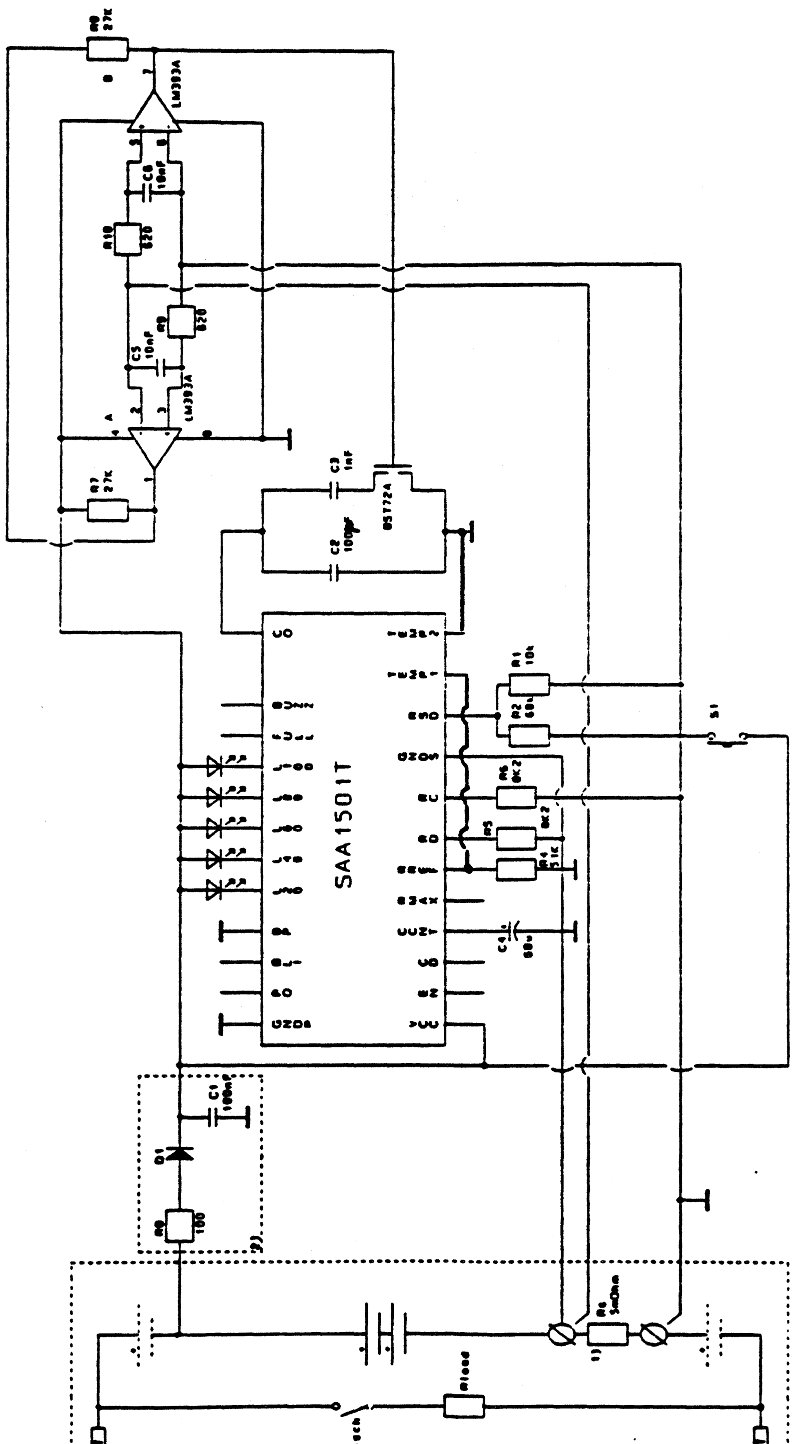
Appendix E

Camcorder Application circuit diagram (section 7.2)



Appendix F

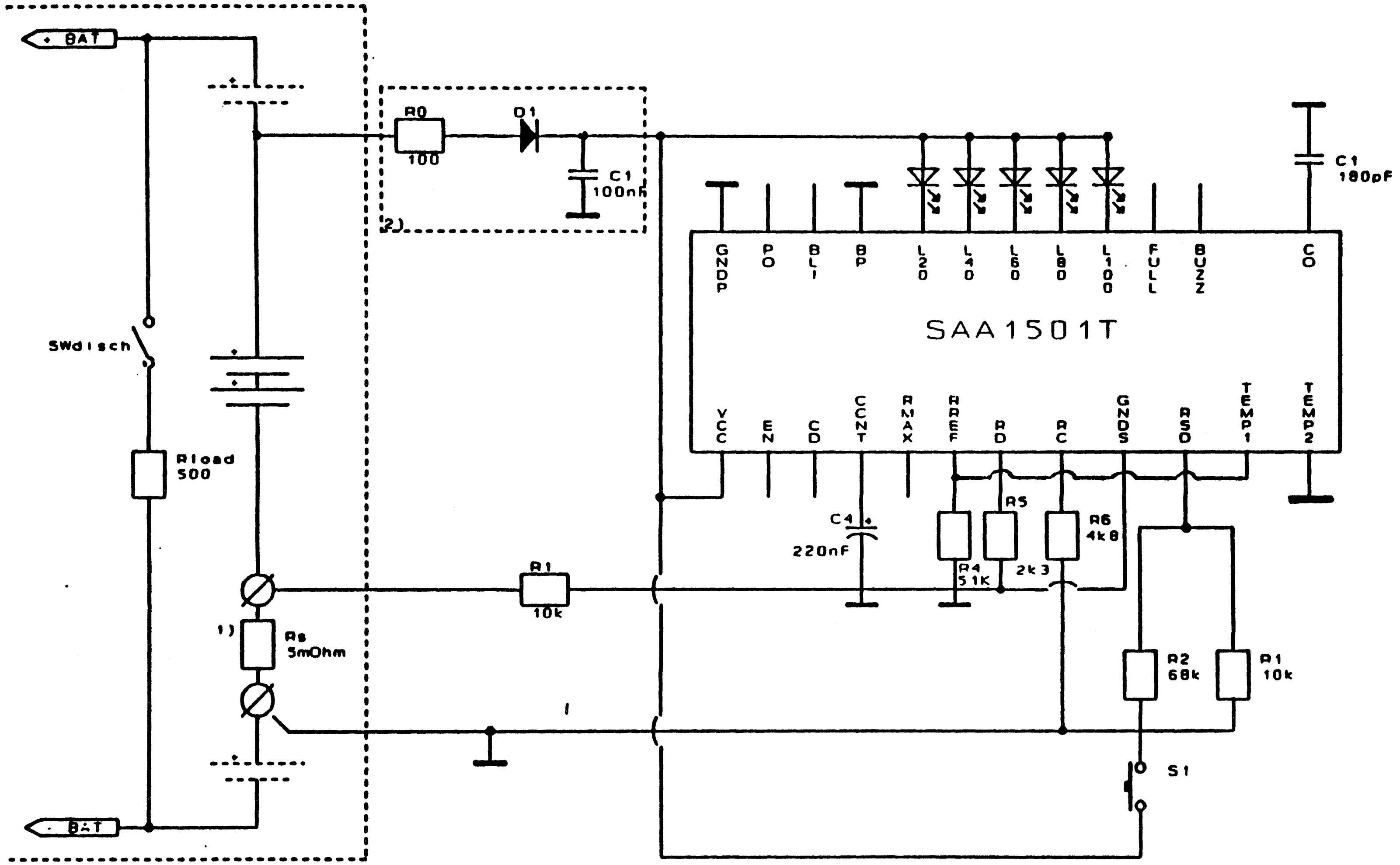
Non-basic tools Application circuit diagram (section 7.3.1)



1) The wire between two individual cells can be used as sense resistor.
2) Use of this 'voltage dip-protection' circuit is optional.
In case this dip-protection circuit is connected three cells - instead of two cells - need to be connected to SAA1501T, because of the voltage drop across the diode and series resistor.

Appendix G

Basic tools Application circuit diagram (section 7.3.2)



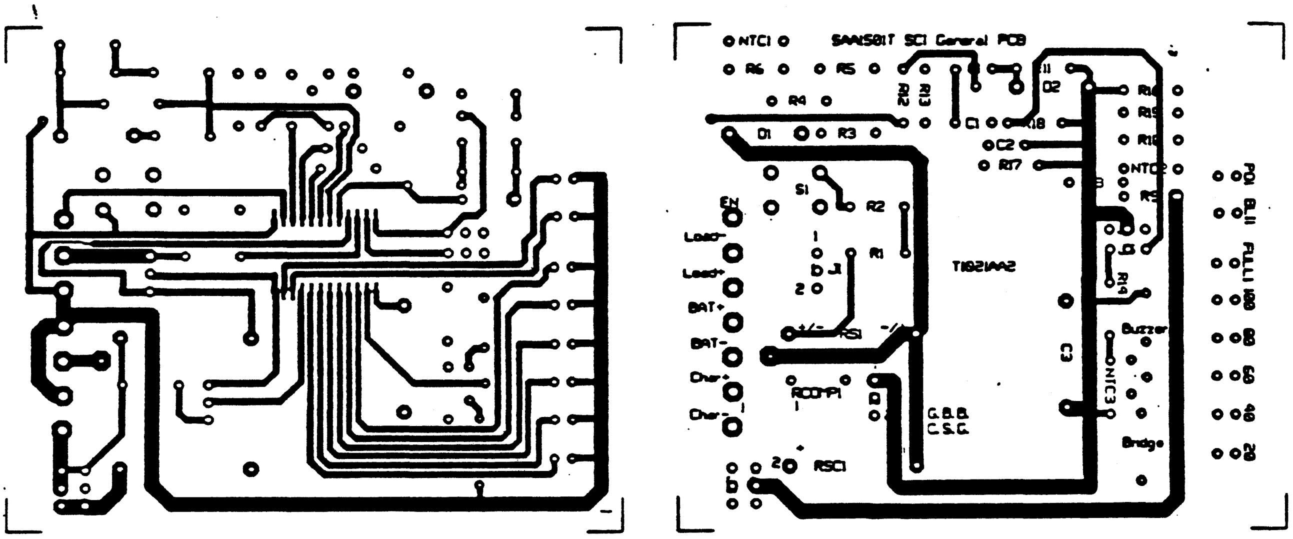
1) The wire between two individual cells can be used as sense resistor.
2) Use of this 'voltage dip-protection' circuit is optional.
In case this dip-protection circuit is connected three cells - instead of two cells - need to be connected to SAA1501T, because of the voltage drop across the diode and series resistor.

Appendix H

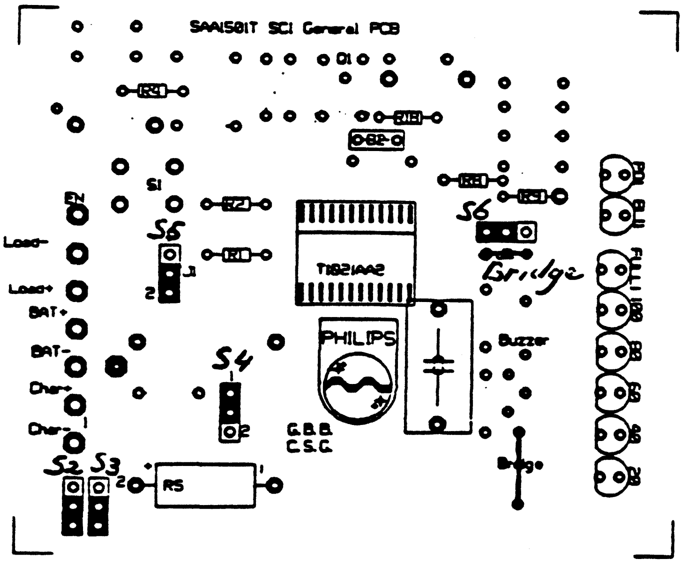
PCB Layout of the Camcorder SCI application

This PCB is for experimental purposes. Only the external components as shown in the circuit diagram in Appendix E have been connected. Other values for Rs, Rc and Rd have been used than those shown in Appendix E.

A) PCB Copper Side (Double Sided)



B) PCB Components Side



Rs	270mOhm
R1	10kOhm
R2	68kOhm
R4	20kOhm
R9	39kOhm
C2	680pF
C3	820pF

APPLICATION NOTE

ICs for Battery Management

Battery Pack Charge Gauge for Camcorders using SAA1501(T)

Report No: NPO/AN9406.

Guido B Banning

Customer & Product Support Group Consumer ICs Nijmegen, Power Conversion Section,
the Netherlands.

Keywords
State-Of-Charge-Indication
Intelligent Battery Packs
Coulomb Counting Principle
Charge/Discharge efficiency compensation

Date : 14 June 1994
Pages: 7

Abstract:

This note is a follow-up on note NPO/AN9401 and deals with a dedicated Battery Pack application for use with a camcorder. Included is a PCB layout for this application. PCBs are available for demonstration or experimental purpose.
For details on the SAA1501T the afore mentioned report should be referred to.

The SAA1501T is a low-cost battery management circuit to be used in fast charging systems. The most important function of SAA1501T is monitoring the charge account in rechargeable batteries. During battery charging the charge current and charge time are registered in a coulomb counter, whereas during discharging the discharge current and time are recorded. The momentary charge account of the batteries can be displayed either on an LC display or by an LED bargraph. In order to get an intelligent battery pack, the state-of-charge indicator function is incorporated into the battery pack.

Dedicated Intelligent Camcorder Battery Pack

The application:
- 5 cells, 6Vnominal, 1.2A*hr batteries (Standard Capacity).
- Charge current range: 1.1A to 1.4A (0.917CA to 1.167CA).
- Discharge current range: 700mA to 1.3A (0.583CA to 1.083CA).
- The application uses one sense resistor only: 70mΩ.
- Consider the battery pack of this application as a black box, i.e. it is not possible to access the single cell voltage with this application thus only the voltage from the complete battery pack unit (5 cells).

1) First examine whether the operational charge and discharge current rates of the batteries are within 0.05CA and 5CA. If so, SAA1501T can operate at its nominal frequency of 4kHz.
The charge and discharge rates are defined by:
Ccharge_rate = Icharge/{Standard Capacity} and Cdischarge_rate = Idischarge/{Standard Capacity} respectively.
Thus, a maximum charge rate of 1.4/1.2 (Icharge_max/QBAT) = 1.167CA and a maximum discharge rate of 1.3/1.2 = 1.083CA are found here. Further, a minimum charge rate of 0.917CA and a minimum discharge rate of 0.583CA are found. The given charge/discharge current rates are thus within range. This means that Fosc can easily operate at 4kHz.

   In this application example for Co a value of 820pF is found (Rref=51kΩ as an Iref of 4μA is preferred), which can be found using formula[12] as stated in note NPO/AN9401.

2) Further, it should be examined whether the sense voltages across Rsense stay within range of the U/I convertors. Preferrably in the range of 4mV up to 400mV.

   Regarding the specified charge current range, with a sense resistor of 70mΩ charge voltages of 77mV (70mΩ*1.1A) up to 98mV (20mΩ*1.4A) will be introduced at the inputs of the charge U/I convertor, which is easily within range of the U/I converter. The same applies for the discharge voltage range at the discharge convertor as with a Rsense=70mΩ a range of 49mV-91mV is found.

   It should be noted that Rsense may not be larger than 286mΩ, otherwise the allowed upper charge voltage is exceeded (286mΩ*1.4A = 400mV) and not smaller than 6mΩ otherwise the minimum discharge voltage will fall below the minimum allowed voltage at the U/I convertor (6mΩ*.7 = 4mV).

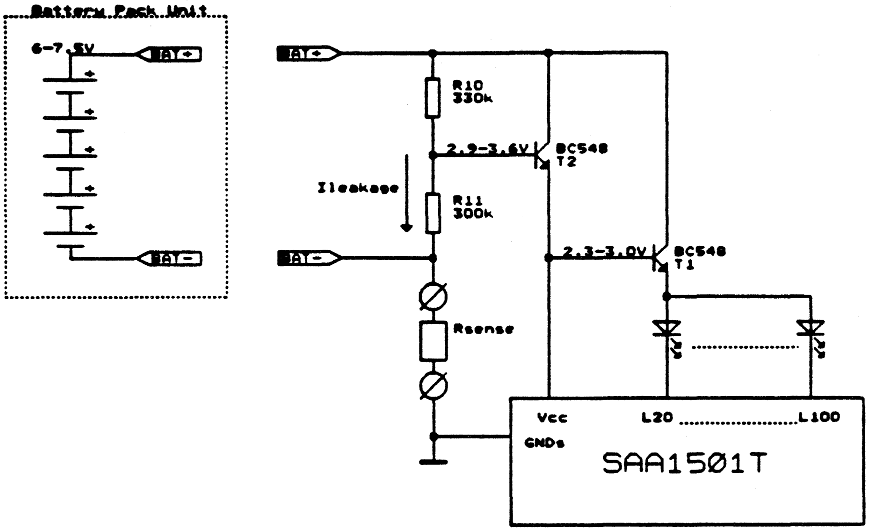
   For an Rsense=70mΩ a maximum dissipation in Rsense of $P_{Rsense} = (1.4)^2*70E-3 = 0.085W$ is found.

3) The values for the charge and discharge converting resistors are found using the formulae in [14] (report NPO/AN9401), in which for the Charge and Discharge efficiency a factor of 70% is used, so that the SAA1501T will operate under-estimated assuring that empty batteries will never occur prior to battery low indication.
Thus for Rc a value of Rc = (1.2*70E-3)/(12E-6*0.7) ~ = 10kΩ is found, whereas for Rd a value of Rd = (1.2*70E-3)/(12E-6*(1/0.7) ~ = 5.1kΩ is found.

4) The minimum value for Ccnt follows from formula[15] (NPO/AN9401), in which it is preferrable to set Iref1 to 10μA (2.5*Iref), as stated in section 6.1 of report NPO/AN9401.
In this application example for Ccnt a value of 0.68μF is found.

To avoid continuous switching of the signal at pin CNT between Vh and Vl, Vh-Vl must be larger than ΔVmax = (Iref1*Tclk)/Ccnt. This is the case in this example: Vh-Vl=0.4V and ΔVmax = 0.24V.

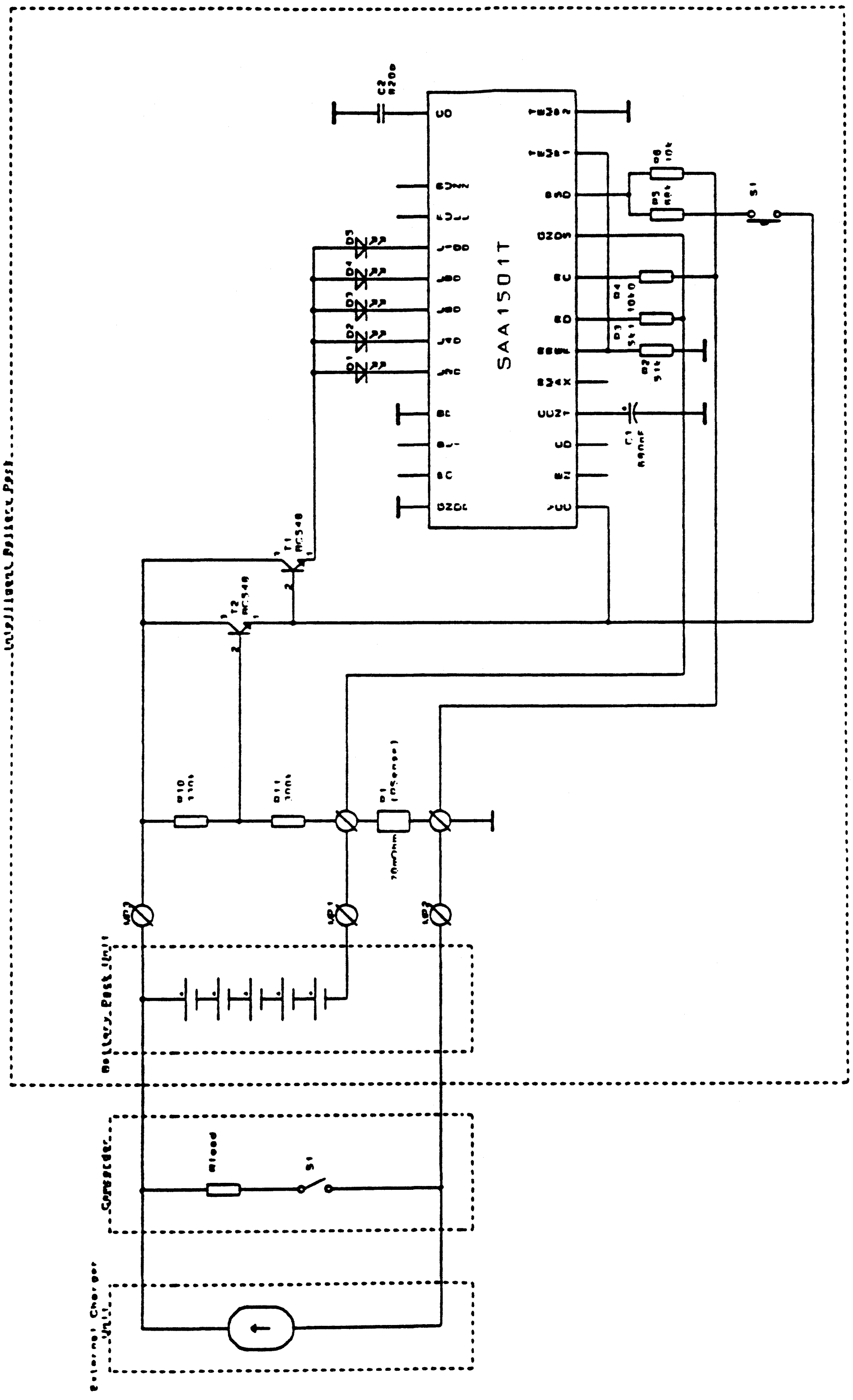
5) As only the voltage (6-7.5V) from the complete battery pack unit is accessible and the SAA1501T operates in the range 2.0-4.5V only, this means that the 5-cell voltage must be divided down. As can be seen in the diagram below the voltage division is carried out by series resistors R10 and R11 which are connected in parallel with the battery pack unit. Then these will cause leakage currents below 10μA, which are negilible compared to the self-discharge currents of the batteries. In order to deliver the supply current for the SAA1501T transistor T2 is used, which can be a simple low-power transistor as Icc< =1.3mA. Assuming the minimum battery pack unit voltage of 6V and maximum battery pack unit voltage of 7.5V the applied Vcc voltage range will be 2.3-3V ((300k/(300k+330k))*Vcc - 0.6V).



6) As the LEDs for the state-of-charge indication at full indication must be sourced with a current of 8*5>=40mA, use of an additional transistor (T1) is required.

Appendix A

Dedicated 5-cell Camcorder Intelligent Battery Pack Application



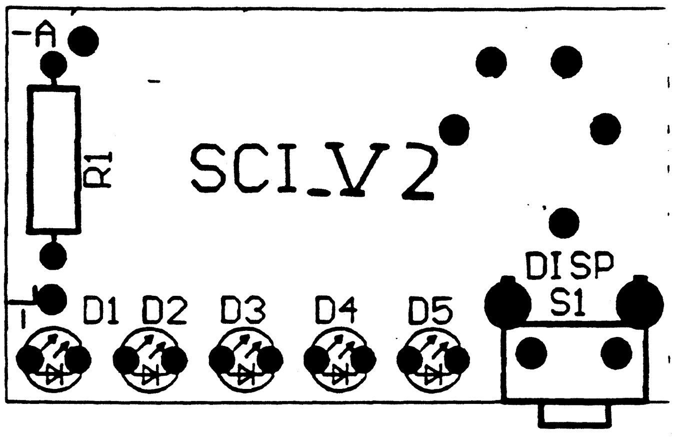
Appendix B

Part list of the application

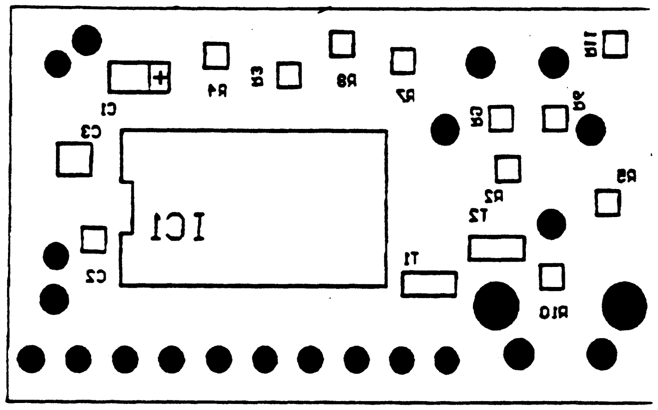
Component Index	Part Nr.	Value	Case	Tol.	Mat.	Vol.
C1	D2022 029 00167	680nF	A	10%	Tantal	20V
C2	D2222 861 12681	820pF	0805	5%	NPO	63V
R1		70mΩ		5%		
R2	D2322 730 61513	51kΩ	0805	5%		
R3(Rd)	D2322 730 61512	5k1Ω	0805	5%		
R4(Rc)	D2322 730 50103	10kΩ	0805	5%		
R5	D2322 730 61623	62kΩ	0805	5%		
R6	D2322 730 50103	10kΩ	0805	5%		
R10	D2322 730 61304	300kΩ	0805	5%		
R11	D2322 730 61334	330kΩ	0805	5%		
T1,T2	D9335 896 40215	BC548C			SOT23	
IC1	SAA1501T				SO24	
5*LEDs						
1*Push Button						

Appendix C
PCB Layout of the dedicated Camcorder Battery Pack Application

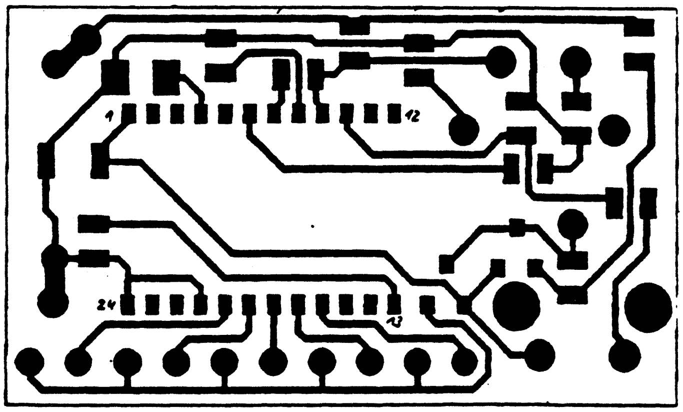
Top view (2.5:1):



Solder-side (2.5:1):



Solder-side: view from the top through the PCB (2.5:1):



APPLICATION NOTE

ICs for Battery Management

Battery Pack Charge Gauge with SAA1501(T) including charge current regulation

Report No: NPO/AN9409.

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the Netherlands.

Keywords
State-Of-Charge-Indication
Charge current regulation
Intelligent Battery Packs
LED current compensation

Date : 15 September 1994
Pages: 7

Abstract:

Note NPO/AN9401 dealt with applications for intelligent battery packs, whereby the charge current control was carried out outside the intelligent battery pack (charge current control was incorporated into the charger unit).

As was mentioned in note NPO/AN9401 already the SAA1501T also includes charge current regulation circuitry to be used for mastering the charger unit, so that the charger unit can be very simple; a simple current source would satisfy. This application note deals with an application making use of this concept, i.e. the dedicated Battery Pack application for use with a camcorder as was described in NPO/AN9406 has been expanded with charge current regulation. Further, the application utilizes another feature of SAA1501T viz. 'LED current compensation' not having been dealt with in preceding application notes.
For details on the SAA1501T report NPO/AN9401 should be referred to.

The SAA1501T is a low-cost battery management circuit to be used in fast charging systems. The most important function of SAA1501T is monitoring the charge account in rechargeable batteries. During battery charging the charge current and charge time are registered in a coulomb counter, whereas during discharging the discharge current and time are recorded. The momentary charge account of the batteries can be displayed either on an LC display or by an LED bargraph. In order to get an intelligent battery pack, the state-of-charge indicator function is incorporated into the battery pack.

Table of Contents:

1 The remaining features of SAA1501T detailed

Two issues ('hiding' features) in the SAA1501T have not been discussed so far. The sections below describe these features in full detail.

1.1 The Charge Current Regulation Circuit

In this section the operation of this circuit is set out (refer to figure 1).
The capacitor Cd (at pin 3) is charged up to VHCd with current {Ic-k*Imax} during time interval t1, and subsequently discharged down to VLCd with current k*Imax during time interval t2 (Ic is the down-converted charge current and Imax is defined by Rmax at pin 5, viz. Imax = 210E-3/Rmax), and over and over again. The SAA1501T has three charge current levels (profiles) and the value of factor k depends on the charge level (status) of the SAA1501T. From the resulting integrating signal at pin Cd an ON/OFF signal at pin EN (pin 2) is derived which is on during t1 and off during t2. When solving the equation Q1 = Q2 by using formula Q = C*U and the currents and time intervals as given in the top part of figure 1, it is found that signal EN will regulate to δ*Ic - k*Imax = 0 (δ = t1/(t1+t2)). This signal is to be used for controlling an external charger or for instance a power transistor. The latter is done with the application in this note.

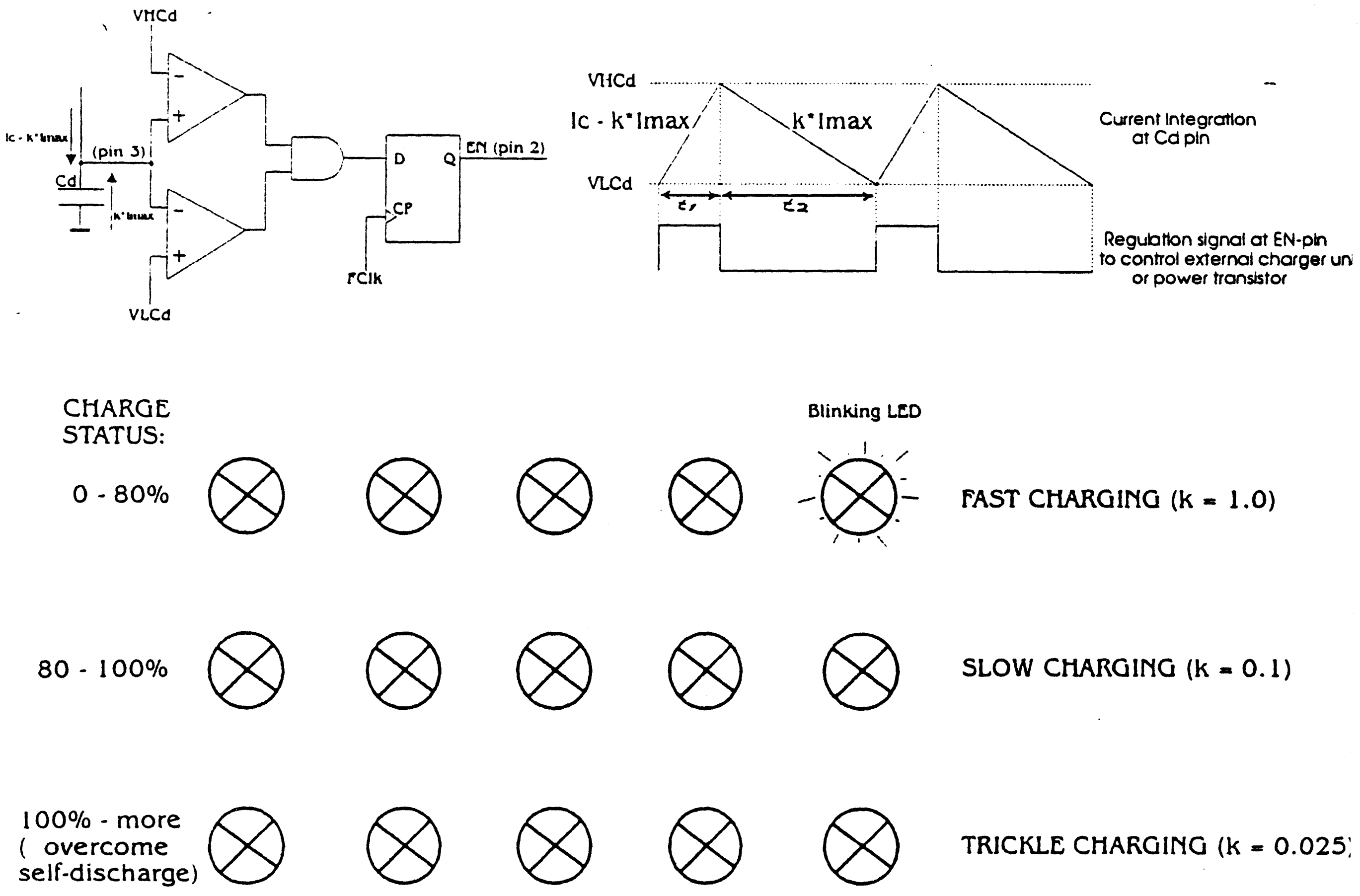


Figure 1: Charge Current Regulation Circuit + LED bargraph visualisation related to the available charge profiles.

1.2 'LED current compensation' by means of signal BP

In NPO/AN9401 it was explained that by means of pin BP the SAA1501T differentiates between LED and LCD mode. Additionally however, in the LED mode the BP produces a so called 'LED current compensation' signal whilst charging when connecting resistor Rcomp and the BP-pin as depicted in figure 2. This way this "additional" discharge current is used to compensate the current consumption used by the LEDs during charging. The mean current value of this signal equals $I_{BP} = N*(I_{LED}/125)$, in which N is a natural number between 1 and 5 depending on the charge status being indicated by L20 to L100. The factor 125 has been chosen so that the down-divided LED-current(s) at BP hardly contribute(s) to the IC's supply current. The 'LED current compensation' signal at BP is a 25% duty cycled signal in order to increase the measure level related to the offset voltage of the V/I convertor and in order to avoid that the SAA1501T will set to the discharge mode whilst charging, i.e. a continuous BP-signal would lead to erroneous influence on the display function.

For designing-in LED current compensation formula Rcomp = 125*Rsense must be used. In the application dealt with in this note therefore a value of 35Ω is found for Rcomp (refer to appendix A).

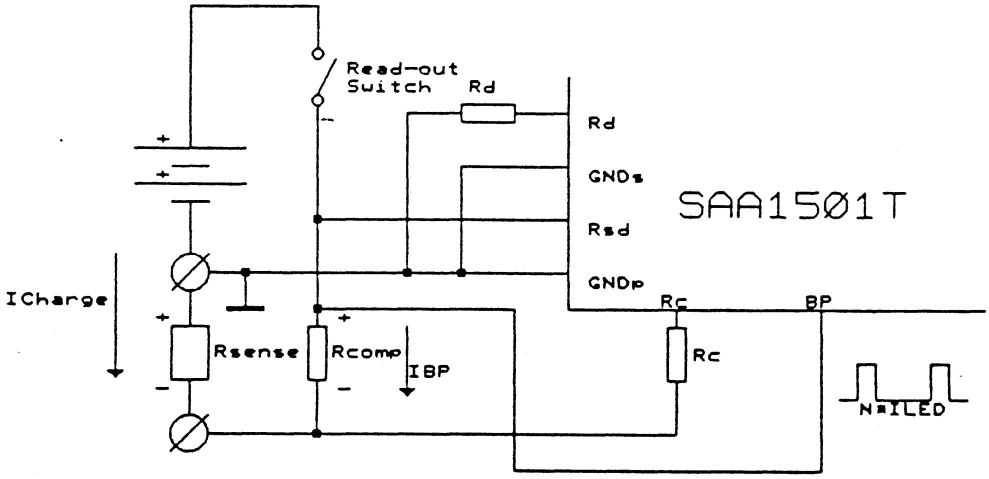


Figure 2: 'LED current compensation' utilized using the multi-functional BP-pin.

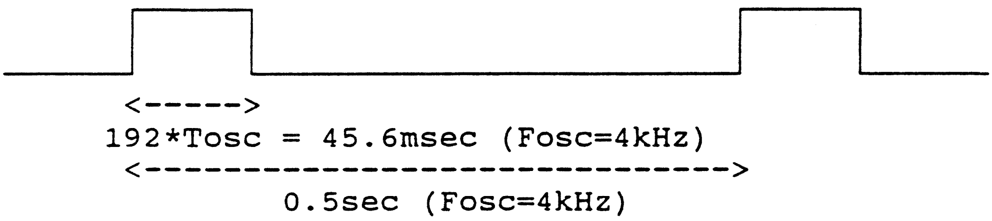
2 Design-in of the Charge Current Regulation function

In this section we will expand 'the dedicated Battery Pack application for use with a camcorder', as was described in NPO/AN9406, with the charge current regulation function, so that the SAA1501T will be in charge of setting the charge current level. This way the external charger can be very simple (no cut-off intelligence); a simple current source would satisfy.
To be able to carry out the design-in (section 2.2) for the charge current regulation function, first full notion of the 'Power Mode Detector'(PMDECT) must be conceived (section 2.1).

2.1 Functional description of the PMDECT

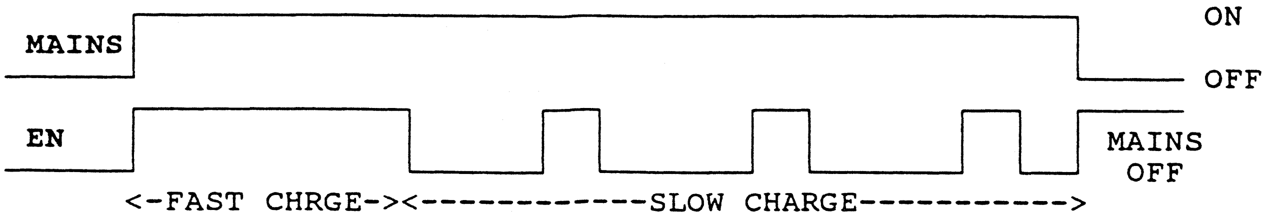
The PMDECT recognizes three modes of operation, viz. the Charge mode, the Discharge mode and the StandBy mode. To save supply current in StandBy mode some circuit blocks in the SAA1501T are switched off including the U/I convertors (for monitoring the charge and discharge currents). To be able to leave the StandBy mode and set to Charge or Discharge mode and thus (re-)activate monitoring of the charge and discharge currents, in StandBy mode the U/I convertors are "sensed" via the 'sense control signal' as depicted below.

'Sense control signal':



Let us now consider the Charge mode only. During the 45.6msec ON-interval of the 'sense control signal', the PMDECT needs to detect an Icharge (Ic) for a time interval >= 8msec (signal EN='1') to be able to set to Charge mode. In the first instance one could think that when choosing the value for capacitor Cd (at pin 3) one should meet the requirement that the ON-time of the EN-signal (which is being derived from the signal at Cd) must be >= 8msec. However, in case that the ON-time in the FAST CHARGE mode >= 8msec - and this is more often the case than not -, the ON-time in the subsequent SLOW and TRICKLE charge modes of the EN-signal may be less than 8msec. This is because then the PMDECT will be able to set to Charge mode during FAST CHARGE and will remain (EN='1') in Charge Mode when the SAA1501T moves to SLOW or TRICKLE CHARGE as t_{ON} < 8msec there is not enough time to detect StandBy mode. In case Power (external current source is switched off) is disconnected, signal EN will remain '1' and there will be enough time (t_{ON} >> 8msec) for the PMDECT to set to StandBy mode (which then should be).
It should be noted that in most cases the charge current regulation circuitry is designed-in so that the ON-time of the EN-signal is 100% during FAST CHARGE.

In short it can be concluded - assuming that the application meets the conditions as given above - that as far as the PMDECT circuit is concerned there is no restriction to the minimum value of Cd. However, as far as the oscillator period Tosc (250μA at Fosc=4kHz) is concerned the minimum ON-time of the EN-signal must be 250μs at minimum (Note that the response time (Slew rate) of the U/I convertors is negligible compared to Tosc). Further, there are no restrictions to the maximum t_{ON} time, however the higher the frequency of signal EN the faster the response time of the regulation loop.



2.2 Application using SAA1501T's charge current regulator

The application:
- Camcorder application as described in NPO/AN9406 (refer to this note for design-in of the 'coulomb counter circuitry' and the 'supply circuitry').
- ICharge = 1A (regulated charge current by SAA1501T in FAST CHARGE mode); ISource = 1.5A (current from external current source). Refer to appendix A for the circuit diagram.

1) Thus in this application example Isource > ICharge. We need to "tell" the charge current regulation circuitry to regulate at 1A (ICharge) so that δ_{EN} will be (1/1.5)*100 = 66.7%. This means that Imax must be equal to Ic during FAST CHARGE:

$$Imax = Ic = \frac{ICharge*Rsense}{Rc},$$

which follows from formula [3] in NPO/AN9401. With ICharge = 1A, Rc = 10kΩ (as was found in NPO/AN9406) and Rsense = 70mΩ, for Imax = Ic = 7μA is found. Thus for Rmax (pin 5) a value of 210E-3/7E-6 = 30kΩ must be used.

2) The value of Cd can be found using formula:

$$Cd = \frac{ICd_{mean}*tEN}{UHCd - ULCd} = \frac{ICd_{mean}*tEN}{0.45} = \frac{k*Imax*tEN}{0.45}$$

$$and\ tEN = \frac{ISource}{ICharge_{regulated}*k}*tON_{\min}$$

When assuming a minimum tONmin = 1mSec for this application example during TRICKLE CHARGE (k = 0.025), we will find a period time of the EN-signal of tEN = 60mSec.
For the minimum demand of Cd (Cd_{min}) it is found that:

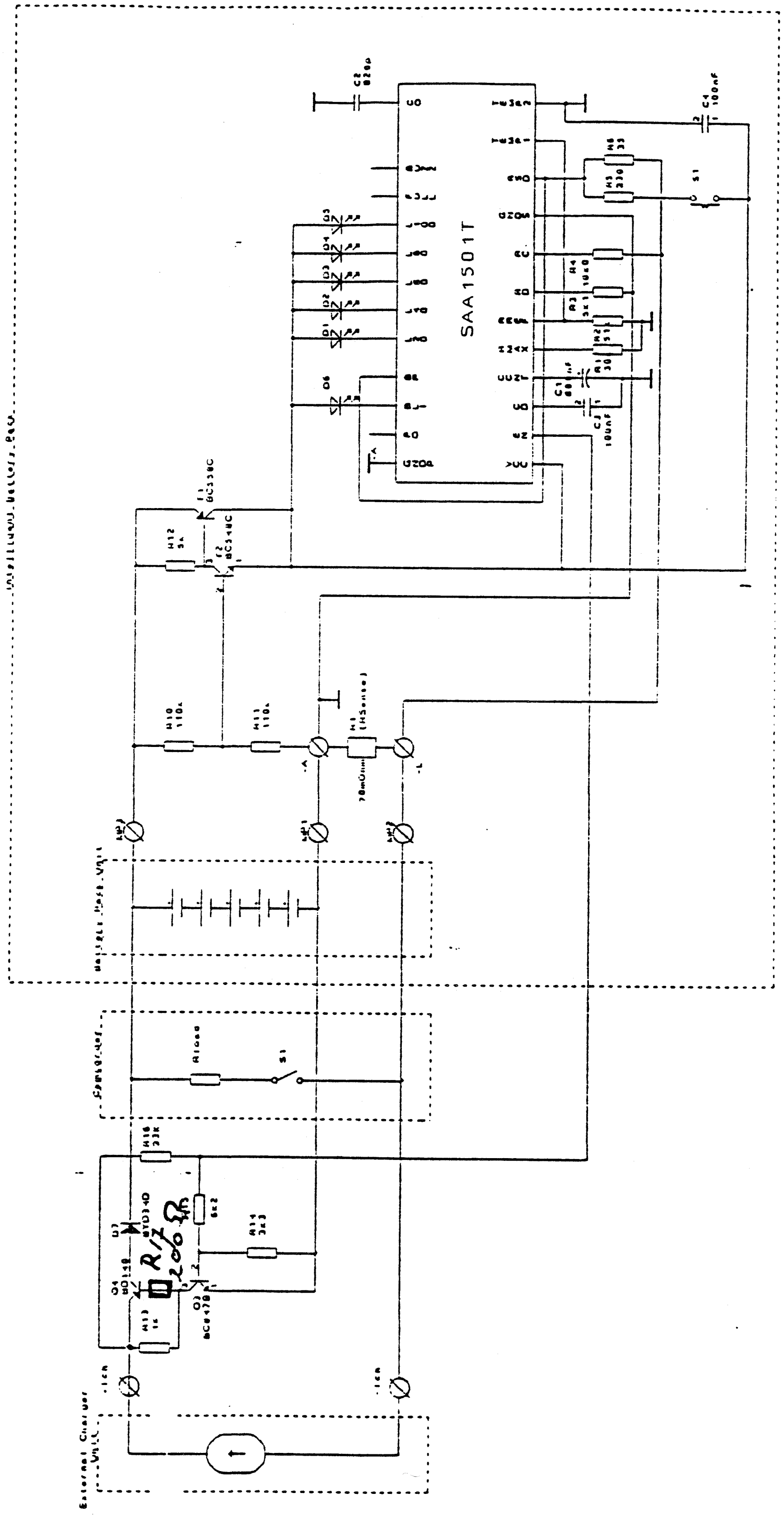
$$Cd_{\min} = \frac{Imax*Isource*tONmin_{EN}}{ICharge*0.45}$$

so that for Cd_{min} a value of (7E-6*1.5*1E-3)/(1*0.45) = 23nF is found. Closest commercially available value for Cd is 27nF.
In SLOW CHARGE mode we then find f_{EN} = 57.5Hz (t_{ON} ~= 1.73mSec (0.1*1/57.5)), whereas in TRICKLE CHARGE mode we then find f_{EN} = 14.4Hz (t_{ON} ~= 1.73mSec (0.025*1/14.4)).

3) The circuitry connected up to pin EN (pin 2) is to control the charge current via power transistor BD140. Resistor R16 is necessary to pull the initially tristated EN-pin to '1'(Vcc) so that FAST CHARGE is activated. R17 is to restrict the current when 0V is applied to the base of the BC847B (transistor which controls the power transistor BD140).

Appendix A

Expanded 'Dedicated 5-cell Camcorder Intelligent Battery Pack' Application



Appendix B

Part list of the application

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R4(Rc)	D2322 730 50103	10kΩ	0805	5%		
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R6	D2322 730 50103	10kΩ	0805	5%		
R10	D2322 730 61304	300kΩ	0805	5%		
R11	D2322 730 61334	330kΩ	0805	5%		
T1,T2	D9335 896 40215	BC548C			SOT23	
IC1	SAA1501T				SO24	
5*LEDs						
1*Push Button						