# POWER MANAGEMENT ELECTRONICS

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## Abstract

Power, energy and battery management cover a common field of expertise that is involved with the supply of power to electronic circuits. With portable equipment, small dimensions, low weight, long operation and lifetime of the on-board energy source are crucial. Efficient power conversion and interaction with the circuits to be supplied can bring down the power consumption. Only through measurement, control and the accompanying algorithms for power management, the targeted performance can be realized. The term management refers to the operation of all functions involved. Knowledge about all contributing parts is at the base of proper power handling and management algorithms. Electronic circuits must provide the means to make it happen. Knowledge about the IC part of electronic circuits is abundant, less is known of the 'bulky' devices as batteries, transformers and large transistors used with power conversion. These devices have a significant impact on size, cost and performance. This paper describes a number of subjects related to such devices rather than the 'how' of electronics and focuses on aspects for IC designers and small portable equipment.

## 1. Introduction

In the past, low power consumption of electronic circuits and efficient power supply of these circuits was hardly considered to be an issue of added value. Nowadays, both with mains-supplied as well as with battery-supplied products, such an approach has an unacceptable impact on product performance and price. Especially with portable electronics as cellular phones and audio players the form factor has become that important that only little room is available for the

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batteries. At the same time, the number of dedicated supply voltages in any apparatus has grown significantly. This ranges from the lowest voltage for small-feature-size CMOS ICs to higher voltages for interfacing to the ‘customers world’ that e.g. dictates high voltage for LCD displays or output power for a loudspeaker or transmitter. Traditional power supply solutions using copper-iron transformers and linear regulators dominated for a long time because of their low cost price. The market does not accept the consequences of their size, weight or losses anymore and thus more advanced solutions became unavoidable. The demand for multi-channel audio power systems drives the application of efficient class-D amplifiers since that allows for the design of slim cabinets.

The mains voltage is the primary source of energy to most equipment. The use of rechargeable batteries grew dramatically because of the high power drain and intensive use of portable electronics.

The user of portable electronics is sensitive to the ‘look and feel’ of the product exterior and thus the electronics inside has to provide performance that allows for attractive design. Miniaturization of energy storage and conversion devices is hampered by many physical constraints. Furthermore, cost price must be low for a competitive solution. Electronic designers are confronted with the total of all aspects involved. Extensive knowledge of the involved technologies and implementation consequences must be made available to designers since they take many decisions that have a significant influence on the final product.

## 2. The Energy Chain

All energy conversion and storage actions imply volume and losses with the accompanying consequences on cost, size, weight etc. Thus, an in-depth understanding of all energy conversion and storage physics and principles is at the basis of advanced power management. For this reason, the whole chain must be considered for allowing optimal design for an attractive product.

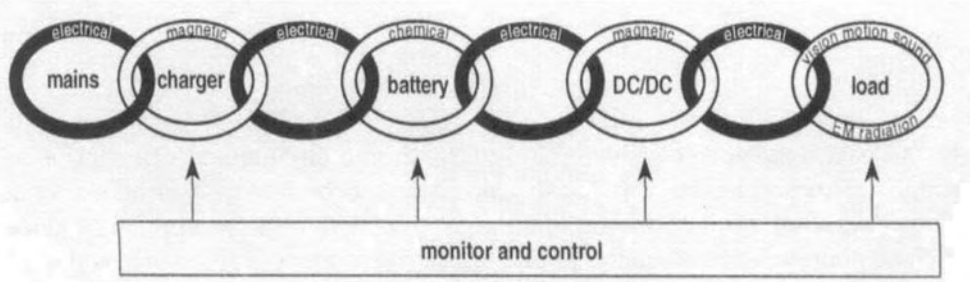

Fig.1. Energy conversion and storage chain.

Mismatch between the available voltage and the required voltage implies voltage conversion that preferably must be done in an energy-efficient manner. A mains power supply has been used for an extensive period of time, since clearly the mains voltage is generally quite different from the required voltage. With battery-supplied equipment, a same structural discrepancy exists between the battery voltage that is generated by electro-chemical processes and e.g. the IC supply voltage that is dictated by the IC-process feature-size and is optimized to a single value.

Energy efficiency of a system is directly related to the conversion and storage actions through the several energy domains. In fig. 1, a so-called 'energy chain' is depicted. This 'energy chain' contains the blocks that physically carry the currents and voltages of the electronic equipment. It shows the energy domains involved in the several parts of a system. In fig.1, subsequently, the electrical energy from the mains is converted via the magnetic domain in a transformer of a charger, then again into electrical energy that in turn is stored via the chemical domain of a battery, then again supplied as electrical energy to a DC/DC converter that applies the magnetic domain and provides the appropriate supply voltage to the actual system that finally has to provide output in the desired energy domain.

The part designated as load represents the whole application that has to be supplied, e.g. a cellular phone or portable CD-player. The energy domains shown in this block are the actual energy domains that provide the actual desired functionality, i.e. light e.g. for data display and video, motion for audio and EM radiation for communication over a long distance.

Underlying, but not depicted in detail, with this 'energy chain' is a significant amount of power management that includes measurement in and control of the 'energy chain' circuits.

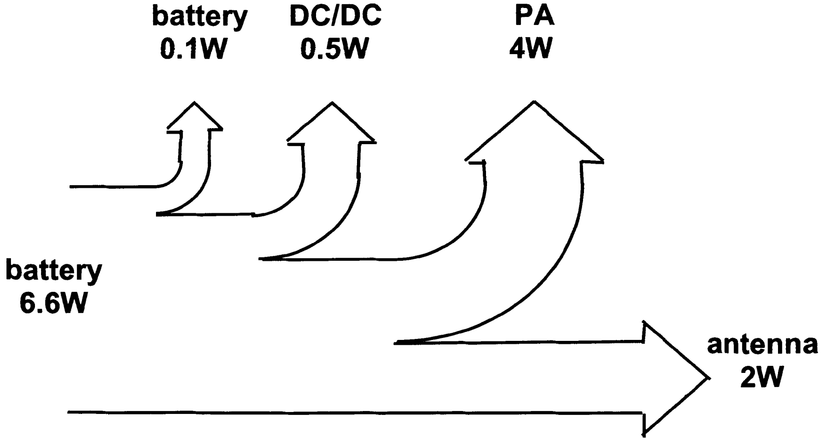

Fig.2. Output power and losses of the transmit part from a GSM phone.

As an illustration of practice, fig.2 shows the power flow of the transmit part of a GSM phone. An overall efficiency of only 30% is achieved from energy stored in the battery to antenna output. The high loss assigned to the power amplifier (PA+) in fig.2 includes the PA, filters and antenna switch. It must be understood that with GSM a saturated PA is applied that has a best-case efficiency of about 60%. With future communication systems, linear PA's are required that have a much lower efficiency. Fig.2 clearly shows that the poor efficiency of the transmitter stage necessitates much higher power levels to be converted and delivered by the battery. Improvements in efficiency at the end of the chain are rewarded by lower cost and smaller size of preceding parts in the chain.

Following the energy chain from left to right, in the past years a number of new means have been provided for the design of power management systems.

- Introduction of an IC process for mains voltages. [ref.1, 2]
- Physics-based modeling of transformers [ref.3]
- Digitally-controlled DC/DC converters [ref.4]
- Physics-based modeling of batteries [ref.5]
- A/D converter with low offset voltage [ref.6]

## 3. Power Management

Exploiting the available energy to a maximum is a useful approach especially when the energy must come from a portable source. Improving the efficiency from 90% to 95% may not be very fruitful from an energy standpoint of view. However, this implies half the losses that need to be accommodated by the several devices. Lower losses allow for smaller size or cheaper packaging.
This latter argument, partly responsible for cost and size, is driving the effort towards very high efficiency.

Apart from providing an optimal power supply in an efficient manner, power management also involves management of power consumption. Supply voltage and bias optimization or enabling circuits only to operate in certain time slots are examples of power awareness in modern systems. Power supply provision and consumption should not be considered as a separate issue, but mutual interaction with the actual system is involved as well.
Power management can reduce losses by providing the optimal bias current or supply voltage, and by switching circuits off when they are idle. Active clock-management can provides an optimal local clock frequency to reduces losses.

Traditionally, the system blocks of the signal path and power supply are independent. An optimal system would also use the actual desired output e.g. the desired light, EM radiation or speed as a feedback to the system blocks. An example of this is depicted in fig.3, where the voltage VDD for the digital circuits is dictated by the application itself in order to run at the lowest adequate supply voltage.

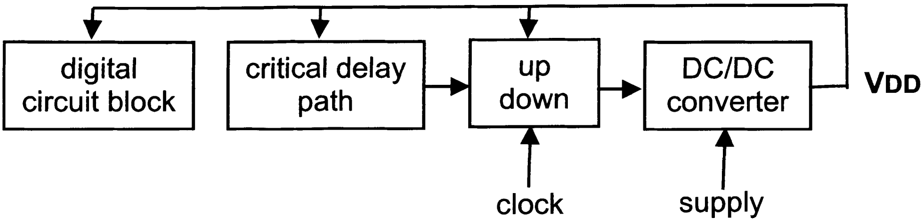

Fig.3. Adaptive power supply for a digital circuit.

The power consumption of digital CMOS is $P = f*C*V_{DD}^2$ and obviously strongly dependent on VDD. A common supply source has 10% voltage tolerance. An IC must be designed for worst-case conditions such that it can operate within a certain process window and temperature range and at lowest supply voltage. For reliable operation the margins of VDD, process and operating conditions must be added, thus leading to tens of percents higher supply voltage than possible with an adaptive supply. In the example of fig.3, the speed of the critical delay path circuit, representative for the critical delay of the digital circuit block that implements the desired function of the IC, is compared with a clock signal. As a result of the comparison, the supply voltage VDD is controlled to such a value that the desired speed of the critical path just meets the required speed given by the clock frequency, and thus, the digital circuit block that operates on the same VDD is guaranteed to provide its function with the proper performance. In this way, the minimum supply voltage for the whole process window and application conditions is generated at minimum power consumption.

## 4. Energy Storage and Conversion

Storing energy is directly linked to volume that in turn is directly linked to price. An amount of energy is expressed in joule or watt*second. The highest energy density is provided by chemistry, both by volume and weight. Well-known examples are combustion of fuel used in cars or for heating and electrical energy delivered by batteries. Demand for electrical vehicles or hybrids is a major driving force in the development of new energy storage and conversion systems. Small portable electronics take advantage from those developments. Passive electrical components as capacitors or inductors have a dramatically low energy storage density compared to batteries. The energy storage density of rechargeable penlight or AA-size batteries has improved about a factor of 4 from the introduction of first NiCd to the current NiMH or Li-ion batteries. A capacitor with a comparable discharge voltage range as a modern AA-size NiMH battery should have the impressive value of about 20 kF. When empty, this battery shows about the same capacitance as a so-called super-capacitor of the same size, i.e. in the order of 10 F.

A power supply unit is traditionally used to accommodate the mismatch between mains voltage and desired supply voltage. Mismatch also exists between the voltage provided by the electro-chemistry inside batteries and the desired optimal voltage. The discharge voltage range from a full to an empty battery is about 40%. CMOS prescribes a specific and accurate supply voltage and some intermediate conversion is required that converts the voltage in an energy-efficient manner. In the past a too-high voltage was provided and the difference was dissipated. Now, for a same reason as the converters for the mains voltage, efficient DC/DC converters between battery and electronic circuits have become common in advanced systems.

Solutions for power conversion use switched-inductor or switched-capacitor techniques. In these converters, energy from the input source is temporarily stored in an inductor or capacitor and subsequently transferred to an output buffer that supplies the load. A continuous consumption of power implies the transfer of amounts of energy at a certain rate or switching frequency. Since only small amounts of energy can be transferred via capacitors or inductors, this has to be done at a sufficiently high frequency. Transistors, either discrete or integrated on an IC, implement the involved switches. Capacitors on ICs have >10% parasitic capacitance to ground while 'floating' capacitors are needed. Furthermore, semiconductor technology is basically a surface technology and thus cannot provide significant on-chip energy storage since the latter requires volume. Increasing the switching frequency is generally linked to higher losses. Therefore, fully integrated power conversion on silicon can only provide limited power. In practice, monolithically integrated charge pumps exist up to the milli-Watt level. For higher power, discrete energy storage devices remain required. Above constraints dictate that devices for energy storage and conversion remain rather noticeable.

## 5. Design Aspects of Power Conversion Electronics

Already for long time, the design of electronic circuits in ICs is performed through software. Both general-purpose circuit simulation packages as well as dedicated software are available for a wide range of performance levels. Especially with IC design, bread boarding has completely become obsolete and processed silicon is in good agreement with simulations. The design of power conversion circuits has lagged in this somewhat. This is partly because of the wide dynamic time range of the circuit techniques involved that provide the required high conversion efficiency. Switching transitions are in the nanosecond range, switching frequency is up to several MHz, loop bandwidth in the tens of kHz range and the supply voltage ripple is e.g. in the 100Hz range or lower during start-up. This has brought about a split-up between circuit simulators that can do 'real-time' time-domain analysis of separate blocks and system-level software that aims at analysis of the function. With the trend to higher switching frequency, it becomes required to merge both and to incorporate accurate real-time circuits in the system-level analysis. For the actual design of the converter itself it becomes increasingly required to model all the parasitic elements of the 'power train', i.e. the circuit parts where the power is handled and the switched current flows. An example for the latter is the VRM (voltage regulator module) for high-end microprocessors. A VRM has to supply e.g. 1.2V@100A within 50 mV window under full dynamic-load conditions. The very high dI/dt involved (100A in a fraction of a μsec, controlled e.g. by a mouse click starting a program) necessitates modeling of every device and mm of PCB wiring down to fractions of nHs and mΩs with great accuracy. The term 'switching noise' used with switched-mode conversion may easily offset small-signal circuit designers since this switching noise may be larger than the supply voltage itself and appears across virtually no distance of wiring.

Efficient power conversion electronics even at lower power levels becomes rapidly unavoidable in a growing range of applications. This brings an increasing part of the design of such systems from power-conversion experts to IC designers. They need better design tools and models that make repeated prototyping superfluous. Accurate compact models suited for time-domain simulations are required, in which knowledge of other disciplines is 'frozen'.

## 5.1 Losses in Electronics

As a first rule-of-thumb, for high power it is recommended to choose a higher supply voltage. In this way, current levels and thus conduction losses are lowest. At the same time, voltage-related switching losses will increase. Requirements of miniaturization of inductors and capacitors ask for higher switching frequencies with accordingly increased switching losses.

Components involved with power handling such as switches, transformers, inductors and capacitors, have properties that introduce losses. Such losses include conduction losses due to resistance in the current path and switching losses due to state transitions in converters. A constant flow of power instead of power bursts provides lower losses. Buffer capacitors handle power bursts and equalize the power flow in other supply paths. For this, it is required that those buffers have a lower equivalent series resistance (ESR) themselves than the current path that they bypass. This requirement may determine the capacitance and size. For comparison of several types of capacitors, one may use a FOM (figure-of-merit) C*ESR.

## 5.2 Switching of a MOS Transistor

The workhorse in power converters is the MOS transistor. In fig.4 a low-side MOST is depicted with a gate drive and load current. Turning on of this MOST can be described as a sequence of time intervals. Fig.5 shows the several time intervals involved during switching on of the transistor, starting from VGS=0 and VDS=VDsup. The root cause of dissipation in every interval provides information on how it can be influenced. Timing diagrams can be made for turning on or off, both for high-side and low-side transistors. At t2, ID = Iload. The gate plateau region (t3 ->t4) i.e. VGS is constant results from the feedback path via CGD when all gate-drive current flows into CGD. During this plateau region (t4-t3 ~ VDsup*CGD/Ig), both high VDS and ID exist at the same time. Normally, a FOM = QGD*RDSon is used for the selection of a transistor that refers to this region were the dissipation is highest. Fig.5 still is a simplified version of practice. Especially with high switching frequencies, the usual FOM becomes inadequate. Aspects involved for better selection or design of a transistor include body diode recovery, non-linear capacitances, internal gate resistance and lumping into more transistors. The gate drive current is supplied from a source with associated losses in the gate drive circuit.

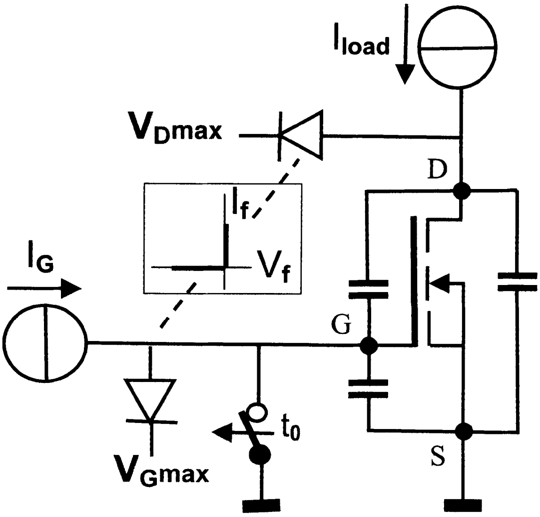

Fig.4. Test circuit for turning-on of a transistor.

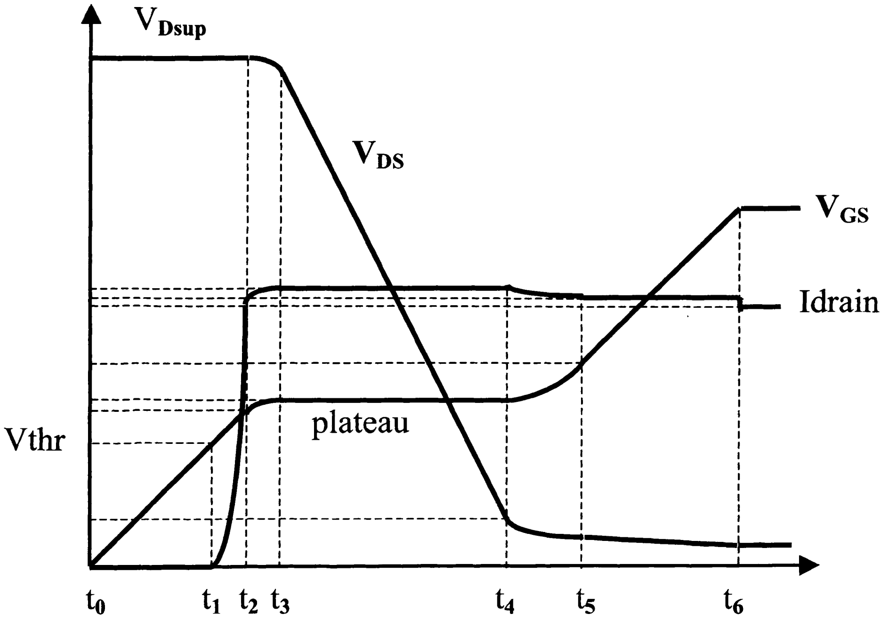

Fig.5. VGS, ID and VDS during turning-on of the transistor in fig.4.

## 5.3 Switched-Mode Power Converters

Switched-mode converters can convert voltages and currents to another value with high power efficiency. These are based on switched-inductor and switched-capacitor techniques. Switched-inductor converters are known in a wide variety of topologies that e.g. convert an input voltage to a higher voltage (up or boost), to a lower voltage (down, buck, class-D) or have a ripple-free output (Cuk). Such converters maintain their efficiency under a variable input/output voltage ratio, because an inductor can store or release energy with low losses independent of the voltage across it. This, together with a control loop that defines the output voltage, makes these converters an attractive solution that is widely applied. However, the inductor remains a relatively bulky and expensive device.

Many textbooks explain topologies, operation and losses of switched-inductor converters. Such converters are strongly non-linear systems with accompanying stability issues in the large-signal domain. Small-signal approaches are used as well for the design of loop stability. The structural impact of size and price many times forces the design of dedicated and optimized converters. Therefore, the design of power converters remains a field of expertise by itself.

Within certain constraints, switched-capacitor converters can have high conversion efficiency as well.

As an example, the properties of a capacitive voltage-doubler or charge-pump are described. The topology and equivalent circuit diagram are depicted in fig.6.

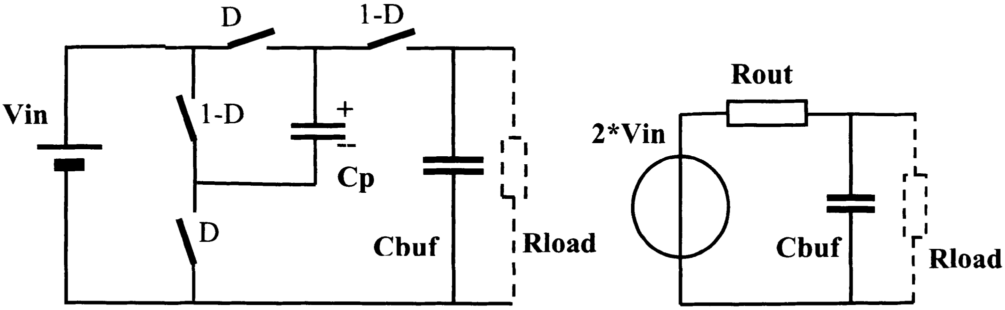

Fig.6. Voltage-doubler with equivalent circuit diagram.

During a time interval D*Tp a pump capacitor Cp is charged via switches by an input voltage and sub-sequentially during (1-D)Tp stacked via other switches on top of the input voltage and connected to an output buffer capacitor that maintains the pumped-up voltage (with Tp being the period time of Fswitch). When the total resistance in charge or discharge path for Cp both equals R, then the output impedance of the charge pump is a resistance Rout of which the value is given in fig.7. The graph shows two asymptotic lines for the value of Rout that can be derived by assuming that Cp << R*Fswitch or Cp >> R*Fswitch and the current through the switches either returns to zero or remains constant in its time interval. The actual value of Rout at the intercept point of both lines is about 30% higher then the intercept value. Assuming only conductive losses in the switches, then the efficiency follows Ohm's law, i.e. $\eta$ = Vout/2Vin = Rload/(Rout+Rload). Varying Fswitch or D changes the value of Rout and enables some output voltage control.

Storing energy in a capacitor from a voltage source via a resistive path is only efficient (Wstored/Wloss is high) when the voltage across the capacitor approaches the charging voltage, i.e. resembling a relatively unloaded condition. This implies a small amount of energy that is transferred every cycle and a large fixed amount of energy stored in the pump capacitor, i.e. effectively a poor energy density. Furthermore, they are only efficient for a certain fixed voltage conversion ratio that is determined by the topology. Constraints for price lead to very low-power applications when fully integrated or otherwise to a number of discrete capacitors with according number of pins to switches on an IC.

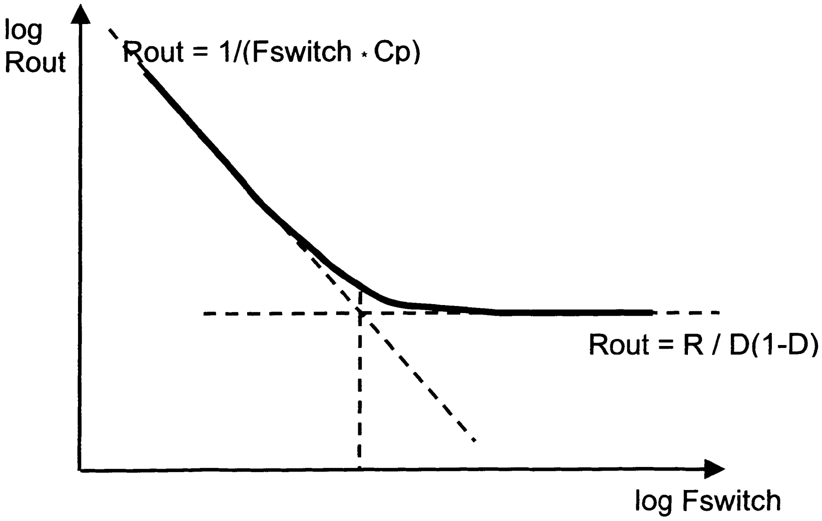

Fig.7. Output resistance of the voltage-doubler from fig.6.

## 5.4 Measurement

For accurate control it is required to have accurate information. In systems where power management is involved, a wide diversity of variables must be observed. Sensors for temperature, pressure, light etc. with appropriate sensor electronics provide the information for the control system. In electronic circuits such information is mostly an electrical signal as voltage or current. The dominant device for accurate current sensing is a resistor that converts current into a voltage. Accurate voltage measurement of low voltages is the basic function for sensor electronics. An analog-to-digital converter has been designed that combines a high bandwidth and a very low DC offset [ref.6]. This ADC is suited for accurate measurement of current, voltage, temperature, or small voltages coming from other sensors. When lower bandwidth is required, lower DC offset can be realized. Offset can also be subtracted in the digital domain. However, large initial offset also implies larger drift.

A reference source is another crucial element in measurement and control systems. Voltage reference circuits (band-gap reference) can be designed in modern CMOS processes that have an accuracy of about 0.5%. Higher accuracy is feasible by on-chip trimming provisions e.g. using non-volatile memory. An example of the application of an ADC for data acquisition for battery management systems is depicted in fig.8. A switch matrix can connect the ADC to measure the battery voltage via R1 and R2, temperature via R1+R2 and R1+T, current via Rs, chip temperature via PTAT, together with a known voltage REF that is used for interpretation of the measured voltages. Shorting the input of the ADC allows for processing of the offset in the digital domain.

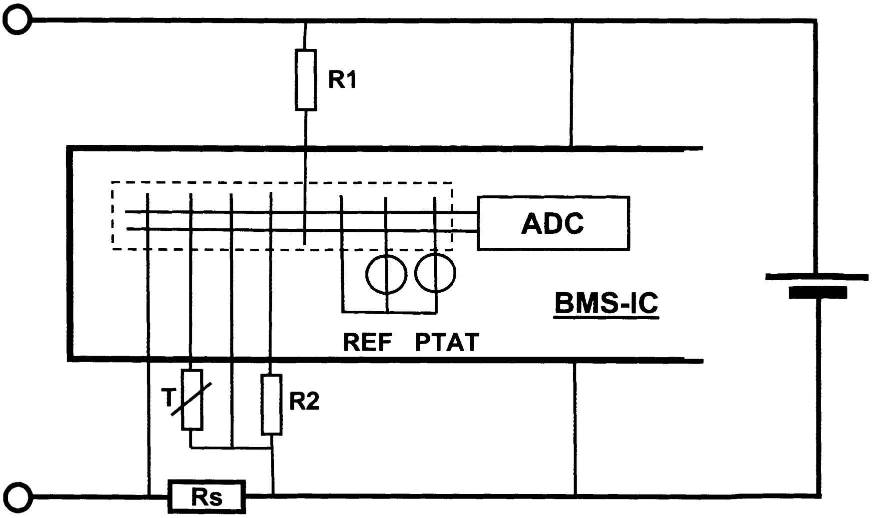

Fig.8. Application of an ADC in a Battery Management System IC.

### 5.5 Partitioning

Handling large current and dissipation directly influences many aspects of the physical design. The wide range of power conversion systems with associated discrete devices and the dimensions of Ls and Cs, heat sink, mains isolation and electronics have a direct impact on the FOM (W/m$^3$) and cost price. This has lead to the development of components with dedicated technology that have a good price/performance ratio. Significant efforts are made to miniaturize or integrate discrete passive components or electronics. However, many times partitioning of the system over separate hardware parts is more attractive [ref.2]. With power electronics, complete integration of the electronics can be attractive for moderate or low power and for systems with limited complexity [ref.1]. High power or current requires distributed heat sinking using discrete devices whereas high complexity requires high-density IC technology such as sub-micron CMOS.

When using high- density CMOS, there is a preference to apply digital circuits only. Ref.4 describes a digitally controlled DC/DC converter with a minimum of analog circuits that makes it attractive for embedding it on digital ICs.

A cellular phone applies several voltage domains: high density CMOS running e.g. at 1.2V, the transmitter running at ~3V and the charger connection must accommodate up to ±20V for a 3.6V battery. An active-matrix LCD module generates its own ±20V for driving the gates of the thin-film transistors.

Power-electronics circuits typically are connected to devices or wiring that can discharge energy in the circuits. Such operation conditions force deviating requirements, especially for IC processes. Especially problems due to the activation of bipolar parasitic transistors can be prohibitive to apply many IC processes. The latter and the increasing amount and wide range of dedicated voltages generates the demand for specific power management IC processes that safely can handle all voltages and currents involved.

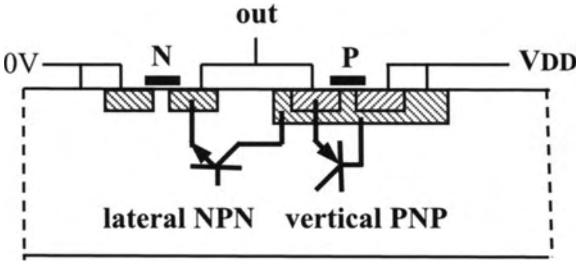

Fig.9. Bipolar parasitic transistors at the output of a CMOS stage.

As an example, fig.9 shows parasitic transistors at the output of an output stage in an N-well CMOS process. In case that both MOSTs are off and current flows into the output, the output voltage will be lifted a junction above VDD and all current is injected with the P-drain/N-well acting as emitter/base of a parasitic PNP. This yields high dissipation; possible offset of other circuit parts and a local voltage drop internal in the bulk that may activate other parasitic transistors. When the current is flowing out of the output, the output voltage is a junction below the bulk and the N-drain/P-bulk of the NMOST acts as an emitter/base of a parasitic NPN. Again, high dissipation, offset of other circuit parts and activation of other parasitic bipolar transistors can occur. Said activation of parasitic bipolar transistors can lead to latch-up. The picture shows only one collector for each transistor. Actually, many nearby regions may act as a collector and other bipolar transistors could already be indicated in fig.9. IC processes suitable for power-conversion output-stages involve vertical stacks of diffusions or oxide-isolation that isolate the devices.

## 6. Physics-based Modeling

The concept of 'power conversion design' is used for two categories. One is the application of existing control ICs with selection of external components for optimization of the performance. The other is the original design e.g. of the control ICs and algorithms themselves or a fully integrated system on chip including the power train and the external components. IC design tools and so-called compact models are available for CAD for IC-design. A compact transistor model is an electronic network and set of equations that replaces a transistor in circuit simulations. Advanced transistor models are based on equations of the physical processes involved, whereas the parameters are based on data derived from physical constants and the IC processing. As a result, models are obtained that are almost unconditionally reliable, independent on their field of application and without being verified in that application. The parameter values are correlated with actual process parameters and statistical analysis over process spread and full temperature range is common practice. Such a design approach is not feasible with bread boarding.

Transistor models and parameters are made available in parallel with IC process development such that circuit designs are ready when a new process is ready for manufacturing. This approach of physics-based modeling allows for a highly reduced design time. The current level of complexity and accuracy of physics-based transistor models for IC design are the result of tremendous accumulated effort. Compact models connect the worlds of semiconductor expertise and circuit specialists. Without accurate models of all parts, trial-and-error hardware evaluation may be required very likely leading to redesign.

Power conversion brings about a number of additional application conditions.

Models of discrete transistors used with power conversion are generally more simple than those used with IC designs. Especially when high switching frequencies are involved, these models become unreliable. Bi-directional current flow in the output can generate signals exceeding the supply voltage. This generally forward biases a parasitic PN junction, e.g. the body diode of a discrete power MOST. With junction-isolated ICs, these PN junctions are base-emitter junctions of parasitic bipolar transistors. Modeling of the parasitic diodes is generally rather basic; the extension of those PN junctions to parasitic transistors is completely lacking in models for IC circuit simulations.

In the field of power converter design, time-consuming hardware evaluation or redesign of electronics was common practice since e.g. no accurate models of transformers are available. In practice, many times one uses behavioral models. However, they only are adequate in a limited range that fit to a specific situation i.e. within the restrictions of a certain operation condition that was already predicted and measured. Behavior models of not-yet existing components can only be rather general. As a consequence, less optimal designs could be brought into production.

Models comparable to those of transistors are also required for devices such as transformers, batteries, fuel cells etc. Then, the expertise and accumulated knowledge becomes better accessible to designers. The common platform is mathematics that can be dealt with by computers. Thus, accurate prediction

instead of confirmation of the behavior of a system can be obtained before a system exists. In addition, a better understanding and verification can be obtained since virtual measurements, even of the internals of a device, and variation of parameters is rather easy and reproducible with simulations.
An advantage of physical modeling is given by the fact that aspects that later in time are studied and understood can be added to the existing model and provides knowledge to optimize the devices.

## 6.1 Transformer Modeling

With the provision of reliable scalable transistor models, the number of design cycles of an IC is drastically reduced. With power conversion however, there is a critical interaction in the design phase with the behavior of transformers and inductors. Compact transformer models that show good correspondence with transformers in practice over a wide application range are rather complex. In practice, simplified models are made with a specific parameter set that is derived from extensive measurements on an existing transformer. The permeability of the core material $\mu$ is normally expressed as function of frequency. This is not suited for time-domain analysis. Generally, non-physical simple models are created and parameterized for a single frequency with non-physical fit-parameters, i.e. some form of reverse engineering.
The creation of a model with parameter set of an existing transformer is already rather complicated. An optimal converter requires an optimal transformer for its purpose together with the design of the electronics. Generating a sufficiently accurate model and parameter set of a non-existing transformer, suited for time-domain simulations, was until recently not feasible for power conversion engineers or IC designers. Ref.3 describes a method that allows for the creation of a model departing from the physical construction (geometrical data, winding data etc.) of a transformer with the derivation of the parameters based on these construction data and material parameter values from physical data handbooks. Transformers are complex devices that show many unexpected phenomena to non-experts. Therefore, some expertise is still required to propose a transformer with a desired performance. However, such expertise can gradually be acquired following the systematic approach from ref.3, since it helps to build up better understanding of the internals of a transformer. The behavior of the proposed component could be verified and applied in the further converter circuit design much earlier than otherwise. Small modifications for optimization may be done departing from the same model and by adaptation only of the parameter values. For large modifications it may be required to generate a new model first. Fig.10 shows the similarity of measured and simulated drain voltage and current of the fly-back converter of ref.1 operating in discontinuous mode.

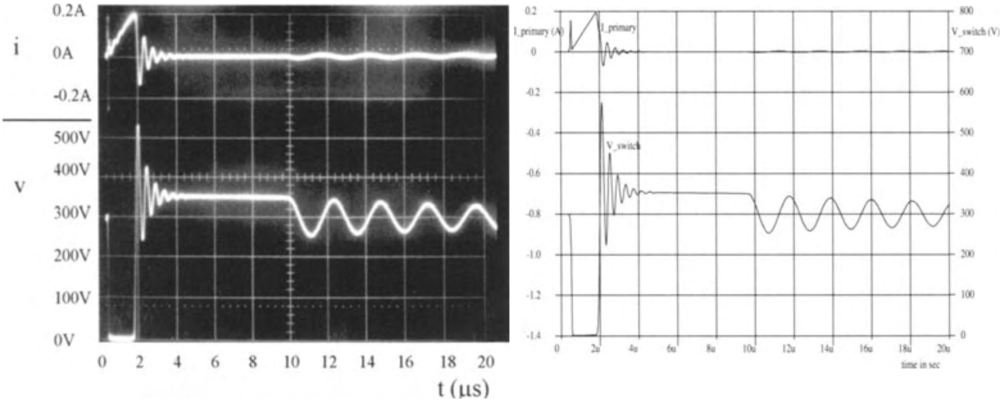

Fig.10. Measured and simulated drain voltage and current.

## 6.2 Battery Modeling

Batteries are the dominant source of energy in portable electronics. A battery is defined as a series of one or more (electro-chemical) cells in series. One can distinguish primary or non-rechargeable batteries and secondary or rechargeable batteries. Rechargeable batteries have become crucial in power management electronics for portable systems. In-depth understanding of their behavior is not a strength of power engineers or IC designers. With the increasing relevance of portable power with the associated complaints about the performance of batteries, it is required to bring the field of expertise of electro-chemistry to electronic designers as well. This is a pre-requisite for optimal exploitation of batteries, both for a single charge/recharge cycle as well as for cycle-lifetime. Knowledge about the state-of-charge, to be applied for charge control or for display to a user, is at the base of 'Battery Management'. Electronic designers can perfectly well apply ICs or design ICs without knowing what is inside the ICs respectively how transistors work in detail. The worlds of electrical engineers and semiconductor experts are connected via compact transistor models. Comparably, the world of electronic engineers and battery experts can be connected via compact battery models that are based on the scientific knowledge of electro-chemists. This approach is rather new and is not yet up to the level of semiconductor solid-state physics with its 50 years of accumulated effort. Chemical processes can be described by mathematics. However, some processes are non-reversible or not yet well known or described and some physical constants are not known to great detail. Also, the morphology of the structure and mechanical and thermal aspects involved make it a big challenge compared to semiconductor physics. The change of performance over life (aging) of batteries is not fully known since that depends on the batteries' history that can be quite different for each battery.

A significant and useful result of the effort is described in ref.5. Even with incomplete models, the impact of different charge/discharge profiles and inside knowledge of state-of-charge or remaining battery capacity can already be studied. The correlation between actual behavior being the result of the several chemical processes, and a driving parameter such as current or temperature is only meaningful with physics-based modeling. Fig.11 shows P,V,T simulation results of a NiMH battery that very well fit with measurements. The physics-based battery model actually provides a virtually transparent battery in which all processes such as energy storage can be observed separately in detail, applying dynamic current in 'real-time' simulations with arbitrarily short time steps. This allows for optimization of the charging and state-of-charge algorithms. It can also be used for fine-tune the chemistry of a battery.

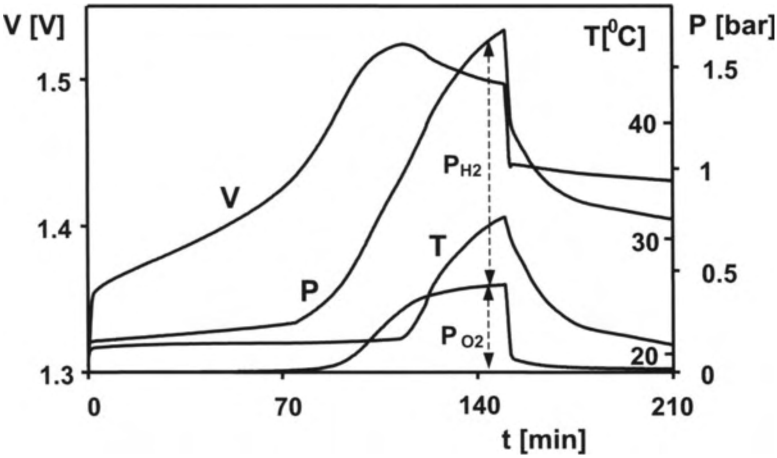

Fig.11, simulation results of battery voltage V, battery temperature T and gas pressure P consisting of $PH_2$ and $PO_2$, during charging and overcharging with constant current (0.55 A) and resting.

## 7. Energy Sources for Portable Electronics

### 7.1 Batteries

Many users perceive batteries as a nuisance. Advise on how to handle batteries to enhance their performance is not a solution. Battery management aims at providing optimal comfort and performance for the user of batteries. This has to be done by electronic circuits and involves optimal exploitation of the stored energy per charge, proper charging algorithms, indication of the remaining charge or operation time and a long lifetime. Knowledge of the state-of-charge, actual capacity, impedance, response to charging etc. form an input for a "Battery Management System" that takes some concerns out of hands of a user.

Rechargeable batteries for small portable electronics are dominantly NiCd, NiMH and Li-ion types.

Fast charging of batteries is a demand in which a balance has to be chosen between charging speed and cycle life of the battery. Overcharging is detrimental to all batteries. Sufficiently accurate knowledge about the state-of-charge is required for proper charge management. The faster a battery must be charged, the more accurate this information needs to be. With NiCd and NiMH batteries, a 'full' battery cannot store more energy and additionally supplied energy is converted into heat. Therefore, the charging process must be terminated. The negative temperature dependency of the cell voltage of NiCd provides information for terminating a high charging current. NiMH does not always have such a negative temperature dependency. Then, the cell voltage is not a proper criterion for fast-charge termination anymore and a temperature sensor needs to be placed against the battery. Li-ion batteries are very sensitive to their charging voltage. Dependent on the chemistry, deterioration occurs at voltages above 4.1V or 4.2V. Additional charge above that voltage is stored, but the associated higher voltage implies a much shorter cycle life. Fig.12 shows the relation between cell voltage, stored charge and cycle life. A too low cell voltage is at the expense of battery capacity, whereas a too high voltage is at the expense of cycle life. It is clear that accurate charge voltage control is required (e.g. ±25mV) when a certain capacity and cycle life must be provided. Li-ion batteries may explode when they are overcharged. In general, Li-ion batteries are only provided as a pack that already includes several safety measures, one of which is a 'safety-IC' that disconnects the battery before it enters detrimental over-or undercharge regions [ref.5].

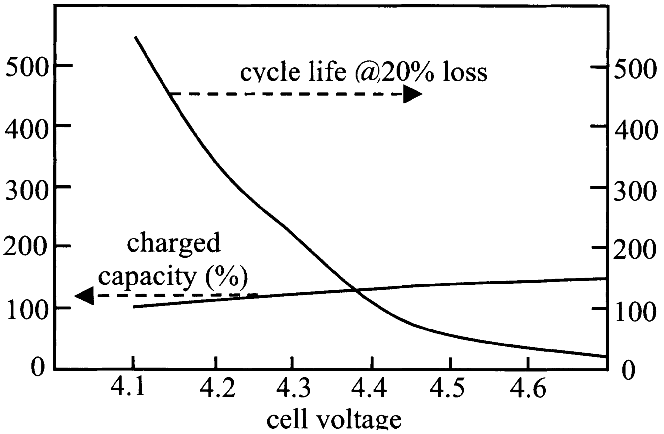

Fig.12. Capacity and cycle life of a Li-ion battery versus charging voltage.

A battery can be represented by an EMF, that is a function of the remaining energy, together with internal impedance. It is common practice to define a battery as being empty when the terminal voltage becomes lower than a certain value. However, the EMF is higher than the terminal voltage and thus still some energy is left in the battery. This can be recognized when the load is switched off and the battery voltage slowly relaxes to its EMF. Said practice is based at the assumption that below that certain value the supply voltage is not sufficient anymore. As a consequence of the internal impedance, battery graphs show a smaller capacity at a higher current. A so-called empty battery still may contain some energy that can be exploited by a DC/DC converter when it accommodates a lower input voltage than the 'empty-battery' voltage.

## 7.2 Photo-Voltaic Cells

Photovoltaic or solar cells can provide electrical energy without being recharged before. The maximum influx of energy on earth from the sun is about 1kW/m$^2$ and the conversion efficiency of solar cells is about 10%. This implies about 0.5W for an area of 5x10 cm$^2$. In less optimal conditions, especially inside a building, where only part of the spectrum of the light passes the window glass, the generated power may be a few orders of magnitude lower.

Solar cells generally are PN junctions and generate a current in parallel with this junction proportional to the incident light. At no-load, the output voltage is determined by the forward voltage of the internal diode at the given current with according temperature dependency given by the well-known diode equation. When short-circuited, the output current is the full photo current. The output characteristic is depicted in fig.13. In this figure, also the maximum-power-point (MPP) is given. The MPP exists where a constant power curve (hyperbola: $V{*}I=Pmax$) touches the graph of the solar cell. With the common silicon solar cells, the MPP is as about at 0.5V. Since this is rather low for the supply of electronic circuits, generally more cells are connected in series. For high power, many cells are arranged in series up to hundreds of Volts at the output.

A switched-mode converter that loads the solar cell can be arranged with a control loop that causes the solar cell to operate in the MPP. When maximum energy must be obtained from solar cells, one must apply tracking to the sun, operation in the MPP and energy storage means (capacitor, battery, thermal store, electrolysis of water as fuel for a fuel cell) to accommodate temporal difference in demand and supply of energy.

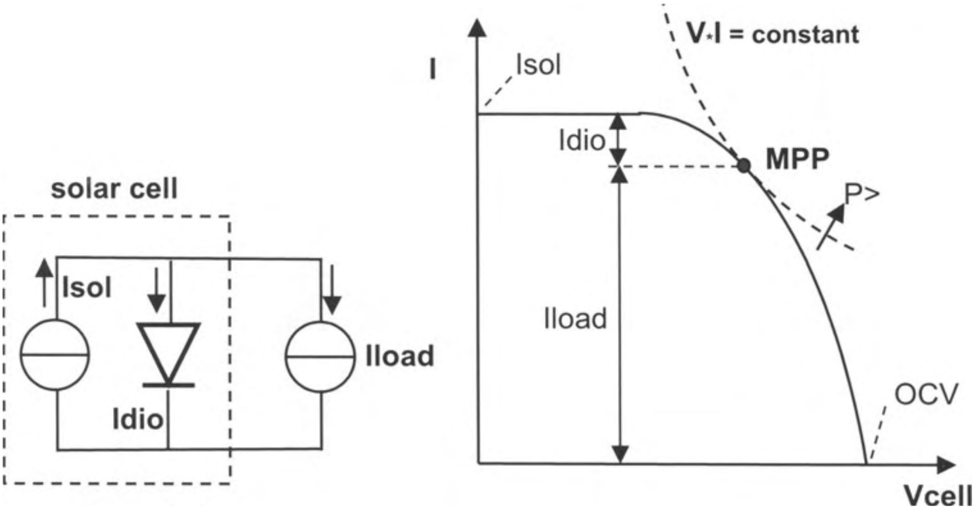

Fig.13. Equivalent circuit of solar cell and output characteristic.

### 7.3 Fuel cells

A fuel cell (FC) is a device that converts the energy of a fuel directly to electricity and heat, without combustion. Since chemical energy is known to have a high energy density and electrical energy without noise is an attractive form of energy, fuel cells attract great interest from many parties. The tremendous growth of portable electronics as laptops and cellular phones and the disadvantages of rechargeable batteries are a major reason for this. However, alternative energy systems like FCs have their disadvantages as well. Fuel cells are already in use in high-power professional applications. Downscaling of fuel cells to lower power has so far not yielded an attractive alternative to rechargeable batteries. Several issues that complicate the use of fuel cells in cellular phones are discussed below.

One could consider fuel cells as small power plants with many operational aspects in common. An infrastructure around the FC is required to provide the proper conditions for the chemical process in the reactor itself. The involved reaction temperature ranges from about 50°C to 1000°C. Isolation of the hot cells to the outside and the fuel storage container both take volume. Flow and pressure of the fuel may involve sensors and electro-mechanical means as pumps or valves and some gas is developed that should be recycled or exhausted, possibly by a fan. The exhaust gas of some fuel cells may be water vapor, but even this is not a trivial matter for cellular phones. The operation of a fuel cell with its supply of fuel, exhaust of reaction products and temperature requirements imply a start-up time and a relatively slow time response. Thus, in practice, a fuel cell needs to be accomplished by another energy store, e.g. a battery with low impedance. The ESR requirement implies a significant size of that energy store. Starting up of a fuel cell system requires e.g. a battery as well.

For portable electronics, it is suggested that DMFC (Direct Methanol Fuel Cell) followed by hydrogen technology will be the most likely types. Since methanol is a more convenient fuel than hydrogen, hydrogen fuel cells can be extended with a reformer that derives the hydrogen from methanol. Fig.14 depicts the principal operation of a DMFC. Supply and exhaust of chemicals need to be managed by sensors, actuators and power management electronics.

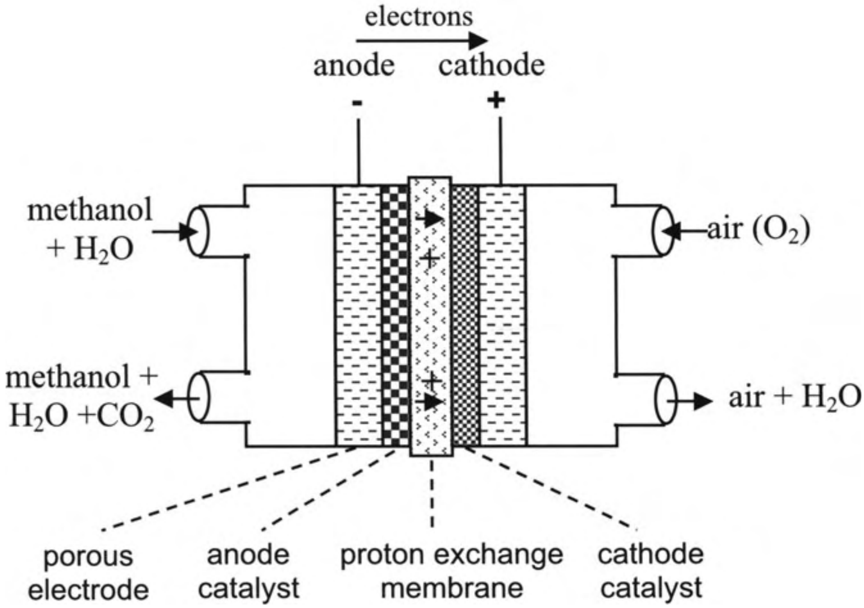

Fig.14. Direct methanol fuel cell: $CH_3OH + H_2O + {}^3/_2O_2 \rightarrow CO_2 + 3H_2O$.

Fig. 15 shows the typical output characteristic of a single fuel cell. An electromotive force (EMF) and complex output impedance can characterize a fuel cell behavior. Per cell, the open-circuit voltage (OCV) is about 1V whereas the useful closed-circuit voltage (CCV) goes down to about 0.5V. The accompanying voltage drop implies losses. The low operation voltage is rather inconvenient for low-cost electronics but may be acceptable for a 1W level. For higher power, more cells need to be connected in series.
A fuel cell is vulnerable for poisoning by contamination. For example carbon-oxide is a poison to fuel cells operating at relatively low temperatures such as the proton exchange membrane FC (PEMFC). Sulfur compounds, present in natural fuels, or air for the oxygen are a major source of poison for FCs.

Severe safety issues already exist with Li-ion batteries. Safety and legal liability are issues for the introduction of FCs in cellular phones as well.

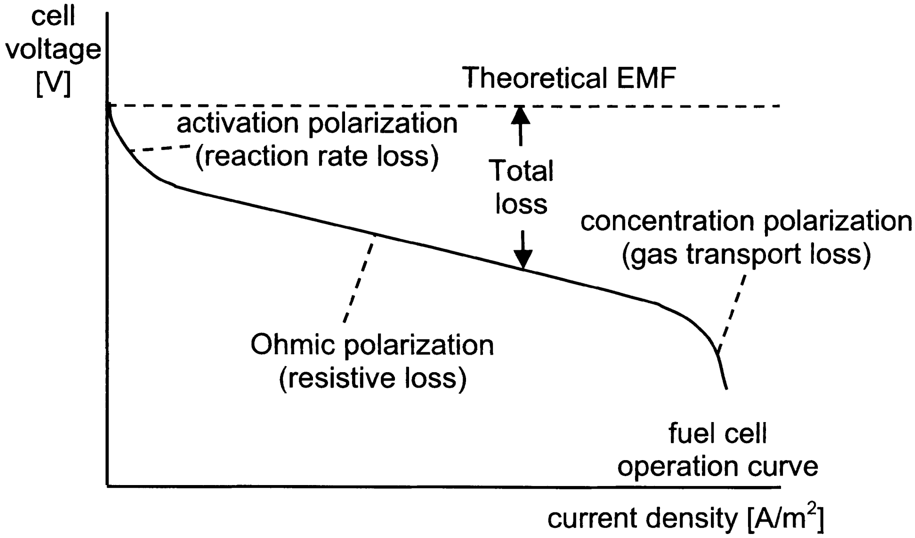

Fig.15. Typical output characteristic of a single fuel cell.

### 7.4 Energy density of energy sources

Overviews of energy systems many times refer to intrinsic energy density, i.e. only the principal technology. In practice, with small dimensions, the overhead of packaging or infrastructure is far from negligible. An advantage of Li-ion chemistry is that it provides a higher cell voltage than NiMH and NiCd and thus allows for fewer cells. This reduces the encapsulation of the cells and housing volume that is quite noticeable with small batteries already. The infrastructure surrounding a fuel cell is significant as well. Scaling down the infrastructure as exists for high-power fuel cells to one for low power raises many challenges.

### 7.5 Losses of energy sources

Energy sources like batteries and fuel cells have internal impedance, i.e. the output voltage drops as the load current increases. Part of this output impedance is just because of passive resistance of materials present in the current path. Another part is because of physical principles that it takes energy to have a current flowing, i.e. a voltage drop to exist.

The voltage that drives the electro-chemical processes that generates the current flow is called the over-voltage. In these processes, several time constants are involved. The time constants show as complex electrical impedance. Normally, CCV (closed-circuit voltage) discharge curves of batteries are provided for a range of DC currents at a certain temperature. These do not provide sufficient information for dynamic current, i.e. having a non-constant profile. An equivalent model of a battery that consists of an EMF source and complex output impedance provides the proper battery response on any load or charge profile. Said EMF and output impedance depend on involved battery type, temperature, state-of-charge and lifetime. Internal losses in the battery exist according $I*(OCV-CCV)$. Comparable issues are valid for FCs.

## 8. Conclusions

Power Management in portable systems is a necessary infra-structural provision for long operation time or small size belonging to the few distinguishing features. Improvements will become default requirements since users are getting used to a certain performance. The demand for additional (power-hungry) features necessitates more complex power management electronics in the future. Power management involves interaction across the whole system level and includes an increasing amount of electronic and non-electronic fields of expertise. An increasing part of the design trajectory of a system shifts to IC designers who are confronted with the design of the whole system. Making the many fields of expertise available in a proper format to IC designers is key to the competitiveness of their designs. Accurate and predictive physics-based models of all components involved, together with a toolset that covers the full design flow are required for a short design time and time-to-market. Due to the direct link between energy, power, size and cost, optimal design of power systems and associated management remains a challenge since it covers a wide range of disciplines.

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