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Guest Editorial

1. Introduction

Today, there is an enormous drive toward low-voltage and low-power integrated circuits, both for analog and for digital processing, and the reasons for this are manifold. In fact, in this Special Issue, two objectives are discussed as if they were one: ''low voltage'' and ''low power''. The reason why these are addressed in combination is that, in many situations, both are required. However, it must be emphasized here that this does not hold for all situations; sometimes only one of them is required, as will become clear from the following discussions.

1.1. Reasons for Low Voltage/Low Power

The best-known argument for low voltage/low power is that more and more electronic equipment must be portable; now that the equipment has become smaller by means of miniaturization, size is no longer an impediment to portability, and this means that the equipment must be battery operated. Also for reasons of size, only one single battery is strived for, which means operation at about 1 volt with minimum power dissipation, in order to enhance battery life.

''Small'' can also be an argument in itself, if the size is limited by the application, as in hearing aids that must be worn inside the auditory canal, or if size is a selling argument, or if EMC requirements demand for small sizes as, for instance, in medical electrode acquisition and transmission circuitry. EMC, however, also demands low emission levels, which means low currents (especially in digital circuits), and thus low power.

Low cost can also be a driving force in the considerations of small-sized equipment with a low battery cost.

The argument of maintenance cost is less well known, but it is especially important in situations where the equipment is not easily accessible, so that replacement is difficult and/or expensive. Here, lifetime is a major point.

Apart from battery lifetime, there is another ground for low power dissipation, namely operation temperature, which influences the operation or even makes operation impossible. In very large processing chips, dissipation, thus temperature rise, is becoming a dominant obstacle which limits further integration density. Operation temperature can also influence the lifetime and reliability of the electronics in a negative way. Leakage currents increase rather fast with rise in temperature.

Scaling down chip dimensions, whereas breakdown voltages are kept the same, means lower supply voltage. This is what is going on in digital circuits: starting from about 15 V in former days for CMOS logic and 5 V for TTL logic, the norm is at this moment 3.3 V; and it is commonly agreed that this specification will also go down, eventually to about 1 V. Also here, there is a direct relation to reliability and life time.

Safety can also be a reason for battery operation, and thus for low voltage/low power.

Finally, environmental arguments (green electronics) push the low-power development, especially for mass products like consumer electronics, as most batteries are known as important contributors to pollution.

1.2. A Definition of Low Voltage/Low Power

From the foregoing discussion, we can deduce that low voltage means about 1 V for both analog and digital signal-processing electronics. Thus, the soft term ''low voltage'' can rather precisely be translated to a more rigid specification. Further decrease of supply voltage can be foreseen in future, possibly up to a few kT/q, but, at the moment, there is no real demand for this. The low power argument is, on the contrary, a rather soft requirement. Here, low power in fact means minimal power, and thus in the case of low voltage it means minimal currents. How low these currents will be depends on the other specifications; in most cases it might be better to speak of relatively low power, or power efficient, than of low power.

1.3. Low-Power/Low-Voltage Applications

During the discussion of the arguments behind low voltage/low power, some applications have already passed in revue. More examples of applications are discussed below, and in a more categorized way.

Portable consumer electronics form a large group; it comprises radios, televisions, telephones, portable computers, personal assistants, personal communication equipment, etc. Here, portability, lifetime, and pollution are the dominant incentives.

Bio-medical electronics form a second group, where size, accessibility, and safety are the primary motivations. To this group belong implantable and injectable electronic devices, as for instance pacemakers, active electrodes, cochlear implants, etc.

A third group is the cluster of electronics with difficult accessibility in oil rigs, satellites, smoke and gas detectors, etc. The service argument is dominant here.

Electronics in dangerous environments require low power dissipation for safety reasons; gauge meters in oil tanks, for instance, have to fulfill rather strict regulations in connection with explosion risks.

Temperature sensors, normally, are meant to measure outside temperature and not chip dissipation, so here also the incentive is the decrease of operation temperature, but now from a functional point of view.

Another application area is that of massive computing by very complex processor chips, where power dissipation (read ''temperature'') and supply voltage are both becoming a limiting factor for further progress in integration density.

1.4. A Global Approach to Low Voltage/ Low Power

Low power and low voltage requirements are, in fact, in many cases derived from system-level requirements such as portability, size, low cost, lifetime, maintenance; only in a few cases are they directly required by the IC, for example in the case of limited breakdown voltage or chip temperature. Thus, in general, the problem is at the system level. There, a distinction can be made between three types of power supplies: mains, batteries, and alternative supplies.

Much work is being done on improving batteries. Although this is not directly the field of an electronic designer, but more the field of physicists and chemists, it is very important to know what is going on in this field, as this will have direct impact on the derived requirements for the ICs. Characteristics that are the subject of research are larger capacity, better rechargeability, increased lifetime, less self-discharging, environment-friendliness, safety, and integration with packages or even chips.

Of course, also alternative supplies are looked at, and have already been looked at for a long time. Photo cells which convert light power into electric power are extensively used; but we can also think of power supplies based on heat differences, as is already seen in watches, or the irradiation of electromagnetic power, received by coils in, for instance, cochlear implants and proximity detectors. The concepts are already old, but they have only been used in a limited number of applications. However, now that electronics power dissipation has been decreased to very low levels, all these ideas are becoming feasible.

Another field of research is that of supply electronics and recharge electronics. For all kinds of supplies, it holds that the interface between the supply and the signal-processing electronics is done by supply electronics, which take care of the supply voltage control, short-circuit protection, up or down transformation, AC-DC converters, battery control for monitoring the battery status, etc. Research is done in all these fields, contributing also to the earlier-mentioned requirements at system level.

Last, but certainly not least, we have the field of low-voltage low-power electronics for signal processing, logic or data processing. Here also, we can look at the problem on various levels. For instance, we can look at filters that dissipate minimal power, given a certain requirement for the dynamic range and for the chip area. However, it might make more sense to relax the filter specifications by changing the system structure. In a radio receiver, this can be done, for example, by changing the detector circuit, or by using a different mixer. However, having a filter structure derived from the specifications originating from the system optimization, we can implement this filter in several ways. A well-known method is using state-space filters, and implementing the states with integrators, each integrator comprising an operational amplifier. These amplifiers, however, dissipate far more power than necessary; dedicated amplifier design will help significantly. Nevertheless, the optimization problem is seen as the optimization of two subproblems, whereas, at least theoretically, there is a better optimization if we optimize the total problem as a whole. As an example, we can take a notch filter. Here, the requirements for the amplifiers, translated from filter specifications, are only stringent at the notch frequency band; at other frequencies, the requirements are far more relaxed. This means that instead of making amplifiers with high bandwidths, we can better make amplifiers with exactly a ninety degree phase shift only at the frequency of the notch. This can be achieved by matching the impedances within the amplifier that are responsible for its time constants with those that are responsible for the integrator time constant. Thus, substantial power savings can be derived.

In all cases, however, we arrive at the level of basic circuits, like amplifiers, mixers, oscillators, bandgap reference circuits, and logic gates. Here, the problem can be countered very fundamentally, as discussed in subsequent papers.

1.5. Ultra-Low Power

Low voltage and low power means voltages in the order of 1 V and currents which are dependent on the application, but which are relatively low, and which go down to currents in the order of micro-amperes or nano-amperes; and corresponding power supply dissipation in the order of micro-watts or nano-watts. Here, some critical limits have been reached, for instance, the maximum resistance value that can be made on chip, or the minimum current through a transistor for which the current models are valid. Such limits are not fundamental, but they are difficult to pass, as new opportunities at circuit level, device level, etc. have to be found to overcome them. As an example of a promising new circuit technique we mention the class of *dynamic translinear circuits*, which will be treated in an upcoming Special Issue of *Analog Integrated Circuits and Signal Processing*. Examples of new devices are the single-electron transistor, the principles of which have been shown lately by physicists, and the silicon-germanium heterogeneous transistor. If the aforementioned currents and supply dissipations can be further decreased substantially, we speak about ultra-low power. This could pave the way for the alternative power supplies mentioned earlier.

1.6. Conclusions

Electronic design is part of a larger system-design problem and must be seen in that context. Low-voltage and low-power specifications are today gaining relatively more attention than the other design specifications, as certain boundaries are approached, and the voltage and power dissipation aspects are becoming crucial parameters for further improvements. Improvements in electronic design imply changes in circuit, device and technology approaches.

As we are coming increasingly closer to the boundaries, the design process is becoming increasingly complex and more difficult to split up into subproblems. Especially now, it is of utmost importance to find optimal design strategies in order to obtain optimal electronic circuits.

2. This Special Issue

It is both an honor and a privilege to be invited to do another Special Issue for *Analog Integrated Circuits and Signal Processing*, dedicated to low-voltage low-power analog integrated circuits. It contains five selected papers that present recent developments in this important field.

The first paper, by G. Ferri, G. Stochino, A. d'Amico, M. Paccio, D. Rossi and G. Ricotti, presents a very low voltage bipolar op-amp for sensor applications. The circuit operates from a single supply voltage as low as 0.8 V and features a 400-μV input offset voltage, a common-mode rejection ratio of 100 dB and an equivalent input noise voltage below 15 nV/$\sqrt{\text{Hz}}$, while the power dissipation is less than 800 μW.

In the second paper ''Low-voltage BiCMOS four-quadrant multiplier and squarer,'' by S. I. Liu, J. L. Lee and C. C. Chang, it is shown that, using cascode NPN and NMOS pairs, a $\pm$ 1.5-V four-quadrant multiplier can be constructed that, when implemented in a 1-μm BiCMOS process, features a $\pm$ 0.8-V linear input range for a linearity error and a harmonic distortion both less than 2%. The bandwidth amounts to 10 MHz for a quiescent power dissipation of only 50 μW.

The third paper, by H. T. Ahn and E. W. Greeneich, presents a 1-V high-frequency bipolar operational amplifier, that, when driving a 10 kΩ load resistance, achieves a unity-gain bandwidth of about 175 MHz with a 50° phase margin. The common-mode input range includes, and can exceed, the negative supply voltage by about 400 mV. A complimentary class-AB type output stage enables the output voltage to reach both supply rails within about 100 mV. The quiescent current consumption amounts to 875 μA.

In the fourth paper ''Ultra low voltage class-AB switched current memory cells based on floating gate transistors,'' by I. Mucha, transistors with floating gates are employed to construct switched current memory cells for 1-V supply voltage operation also in CMOS processes with threshold voltages of about 0.9 V and − 0.9 V for the N- and P-channel devices, respectively. A thorough analysis of the major impacts degrading the performance of the proposed memory cell is given. As an example, a 1-V class-AB memory cell is presented that allows a signal range larger than $\pm$ 18 μA for a quiescent current which can be as low as 1 μA.

Finally, the fifth paper, by A. van Staveren, G. L. E. Monna, C. J. M. Verhoeven and A. H. M. van Roermund, presents a low-power class-AB negative-feedback output amplifier for a 1-V LW receiver. The amplifier has been integrated in a bipolar process ($h_{fe,NPN} \approx 100$, $f_{T,NPN} \approx 5$ GHz, $h_{fe,LPNP} \approx 75$ and $f_{T,LPNP} \approx 20$ MHz). Its maximum output current is approximately 2.5 mA, while its quiescent current is as low a 100 μA. When driving a 30-Ω load with a 1-kHz, 1-mA signal, the total harmonic distortion is less than 1%.

The editors would like to thank all the authors who submitted papers, all the reviewers who participated in the final selection of the papers, and the Kluwer Editorial Staff for their efforts in creating this special issue. We hope that this second issue will provide you, the reader, new insights into the potential of low-voltage low-power analog integrated circuits.

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Wouter A. Serdijn was born in Zoetermeer, The Netherlands, in 1966. He started his course at the Faculty of Electrical Engineering at the Delft University of Technology in 1984, and received his ''ingenieurs'' (M.Sc.) degree in 1989.

Subsequently, he joined the Electronics Research Laboratory of the same university where he received his Ph.D. in 1994. His research interests include low-voltage, ultra-low-power, RF and dynamic-translinear analog integrated circuits along with circuits for wireless communications, hearing instruments and pacemakers. Since 1997, he has been a project leader in the multi-disciplinary Ubiquitous Communications (UbiCom) research program of the Delft University of Technology. He is co-editor and co-author of the book *Analog IC Techniques for Low-Voltage Low-Power Electronics* (Delft University Press, Delft, 1995), and of the book *Low-Voltage Low-Power Analog Integrated Circuits* (Kluwer Academic Publishers, Boston, 1995). He has authored and co-authored more than 40 publications. He teaches Analog Electronics for Industrial Designers, Analog IC Techniques and Electronic Design Techniques.

Chris J. M. Verhoeven was born in the Hague, The Netherlands, on February 25, 1959. He received the M.Sc. degree in electrical engineering from the Delft University of Technology in 1985. In 1985 he joined the Electronics Research Laboratory of the same department in order to prepare a Ph.D.

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At present he is an associate professor at the Electronics Research Lab. He is the project leader of the group ''Structured Electronic Design'', in which design methodology for synthesis of analog basic circuits is addressed. To date the main topics are wide band amplifiers, bandgap references and oscillators, with an accent on low power and low voltage circuits for RF, and also optimal application of technology. The topics in this field are the application of SiGe technology in exponential low-power RF-circuits and application of Single Electron Tunnelling technology for implementation of efficient neural devices.

Albert C. van der Woerd was born in 1937 in Leiden, The Netherlands. In 1977 he received his ''ingenieurs'' (M.Sc.) degree in electrical engineering from the Delft University of Technology, Delft, The Netherlands. He was awarded his Ph.D. in 1985.

From 1959 to 1966 he was engaged in research on and the development of radar and TV circuits at several industrial laboratories. In 1966 he joined the Electronics Research Laboratory of the Faculty of Electrical Engineering of the Delft University of Technology. For the first 11 years he carried out research on electronic musical instruments. For the next eight years his main research subject was carrier domain devices. More recently he has specialized in the field of low-voltage low-power analog circuits and systems. He teaches design methodology.

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First he worked in the Consumer Electronics Group on design and integration of analog circuits and systems, especially switched-capacitor circuits. In 1987 he joined the Visual Communications Group where he has been engaged in video architectures and digital video signal processing. From 1987 to 1990 he was project leader of the Video Signal Processor project and from 1990 to 1992 of a Multi-Window Television project. Since 1992 he is a full professor at the Electrical Engineering Department of the Delft University of Technology where he is heading the Electronics Research Laboratory. He is also group leader of the Electronics Group and co-ordinator of the Circuits and Systems Section of DIMES, the Delft Institute of Micro Electronics and Submicron technology, which is a co-operation between research groups on microelectronics, technology and technology related physics.