Abstract - The early DC/DC power converters consisted of DC/AC/DC circuits, using electromechanical choppers, ferrite core transformers, and rectifiers. They were: inefficient, bulky, heavy, and not suited for portable microelectronics. By eliminating the AC transformers and using only switched capacitors, the exceptionally efficient, lightweight, small, and nowadays worldwide used "charge pump" emerged. The birth and the evolution of the charge pump from its first appearance on the 1964 ETAN to the intense surface mounted regulated output DC power supplies, is described.

1. INTRODUCTION

About 100 years ago, the pioneers of electrical energy, Tesla and Edison disagreed about the advantages of AC over DC power. Tesla won and the AC powers most of the world today. Streets and cities are now loaded with AC transformers.

On the other hand, for the battery powered devices there was no other known solution for conversion of DC power to higher or lower voltage, but the motor-generators (alternators), or the DC/AC/DC conversion, by electromechanical choppers and heavy transformers.

Lately, new stabilized DC output power supplies are offered, where the output is controlled by the switching frequency. Their small size and very high efficiency make them useful for all kinds of power management, in the ever-shrinking size of portable electronics of the new century.

Charge pumps offer several advantages over switches in low current (<100 mA) applications. Reference [1] lists 54 (just a few, really) abstracts of the recently published charge pump related papers.

2. CRASH COURSE IN CHARGE PUMP THEORY OF OPERATION

The transfer of charge is essential for the charge pump function. Charge pump operate by first storing energy, then releasing this energy in a controlled manner to achieve a desired output voltage. Charge pumps use capacitors to store energy. Figure 1 shows simple block diagram for a capacitive charge pump converter. The internal oscillator becomes active only when the output voltage is lower than its threshold. This regulation ensures the circuit to provide constant output voltage and, at the same time, it draws minimum currents at light loads.

Figure 2 describes the charge transfer process. Once the transfer of charge is understood and available, numerous architectures are easily structured. Capacitor C2 from Figure 2 is traditionally called the "floating capacitor".

![Diagram of charge pump block diagram](image1)

![Diagram of charge pump operation](image2)
Thus, the Cl transfers the finite amount of charge to C2 (Step 1), and then C2 connects to C0 (Step 2), and transfers charge to it. If Step 1 and 2 are repeated a sufficient number of times, the voltage across C0 approaches that of the C1.

The charge transfer has enabled the construction of voltage generators and a large number of other applications, of which the voltage doubler and splitter are the simplest. Figure 3 shows the application of charge transfer in voltage splitting.

Figure 3. The voltage doubling (splitting) utilizing the charge pump principle. V1 - input voltage; V2 - output voltage; I0 - output current; C1, C2, C0 - capacitors; S1, S2, S3, S4 - switches; Vx is the constant input voltage. (Courtesy of Maxim, Inc.)

The charge pump tries constantly to maintain equal voltages across C1 and C0. This attempt essentially halves the input voltage equally between capacitors. Every drop in output voltage V0 is compensated by an equal and opposite drop across C1. In that way the voltage splitter gains a factor of two in output resistance. And this is another useful property of this circuit.

3. CHARGE PUMP EVOLUTION

The birth and development of charge pump, from the inception in Yugoslavia to its world-wide acceptance, went along the following lines:

- It first appeared in public as the 1963 Yugoslav patent application. The patent is awarded for the invention of the Charge Pump. [4] is the facsimile of the original Charge Pump patent release. Two young engineers submitted the patent application to the SFR Yugoslavia Patent and Trademark Office on June 18, 1963: Miodrag Novakovic and Bela Kovach. The patent application was awarded the Priority Option on November 21, 1963. Charge Pump patent became effective on June 30, 1964, and was released later in the year, on December 31, 1964. The patent release proved that the Charge Pump idea presents a significant, original contribution. It was also awarded the Gold Medal at the 1964 Brussels Inventors Fair [8]. The release of the patent paved the way for what will be called in 2001, almost 40 years later: The Charge Pump Explosion.

- One year later, the paper describing the charge pump was presented at the 1965 ETAN conference [5]. In addition to the qualitative essence of the invention, already available through the Charge Pump Patent Release, the paper offered the mathematical treatment of the invention, and described the actual charge pump implementation in detail. This paper brought the Charge Pump concept out to the engineering community.

- The same 1965 year in November, the popular Design News magazine published the article on the charge pump [6], directly referencing Yugoslav authors M. Novakovic and B. Kovach. This is the U.S. magazine for bringing the electrical/electronic news. The DN Overseas Editor, a person in charge of looking out for new and good things overseas, i.e., in Europe, Yugoslavia included, wrote the article titled "Capacitive Transformer Doubles D.C. Voltages". This is the earliest U.S.A. reference to this Yugoslav invention, and its authors, Miodrag Novakovic and Bela Kovach. The article also carries a warning: patent applied. The DN magazine is read around the world. Every engineer interested in power supplies, portable electronics, and low power - high efficiency applications started to experiment with the charge pump.

- About 20 years later, the first integrated circuit implementation followed [7]. Less than 20 years after its invention, the charge pump became available as the medium scale integrated, inexpensive circuit. It became relatively easy to design and implement voltage converters using capacitors only. The IC implementation of the charge pump opened the door for thousands of portable, high efficiency, low weight, and high reliability (due to the low component count) applications.

4. CHARGE PUMP CONCEPTS

This section briefly outlines the most important characteristics relevant to the charge pump.

Due to its switching nature, the charge pump provides for the semi-conductor isolation. It also offers a certain level of protection from output overload. It is frequently used for the generation of negative voltage (inverting). Input/Output separation also offers some voltage stabilization. However, one of the most popular function is the voltage doubling. Using the charge pump to triple the voltage (and above) is not as unusual. Typical frequency of operation has not changed for almost three decades; until recently, most implementations used the 10 kHz frequency, originally proposed by the charge pump inventors [4]. The same holds for typical capacitances: they've been kept at 10 μF. Lately,
in an attempt to 'squeeze' capacitors inside integrated circuits, frequency has gone up [2].

The basic phase-lock-loop configuration (Fig. 4) consists of a crystal reference oscillator, a frequency synthesizer, a voltage controlled oscillator, and a passive loop filter. The frequency synthesizer includes a phase detector, current mode charge pump, and programmable frequency dividers. Here, the current charge pump is used as a phase detector. It pumps charge into the loop filter, which in turn converts the pumped charge into the VCO's control voltage.

![Figure 4. Basic charge pump Phase Locked Loop - PLL (Courtesy of National Semiconductor)](image)

For very low supply voltage systems, typically powered by silver oxide batteries, charge pumps raises voltage to the sufficiently high level (2.6 V, 3.3 V), so the CPU's and other digital electronics would operate. Its very high efficiency (up to 90%) is rather desirable for the low supply current systems. Very simple and robust PLL (Phase Locked Loop) structured employ the charge pump as the phase detector. There are on-line tools available for the selection and design of charge pumps [3].

6. CONCLUSION

It is the popular belief is that improvement of technology are the monopoly of the most advanced countries. The fact of the matter is that good ideas are born often at seemingly unimportant places, and the advanced countries are usually capitalizing on them only, the Charge Pump invention being the prime example.

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The authors would like to thank the ETAN for nurturing the spirit of innovation over many years of adversities. We would also like to encourage young engineers to continue to support this forum, by presenting their new ideas for the benefit of the world and for the respect of the society they are coming from.

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