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Good Vibrations Power Wireless Sensors for ‘Fit and Forget’ Battery-Free Condition Monitoring

Energy harvester converts vibration into energy; supporting supercapacitor stores energy & delivers power bursts to transmit data

Introduction

This article describes a machinery condition monitoring system developed by GE Energy for a field trial in the challenging industrial environment at the Nyhamna gas plant in Norway. We will concentrate on the power supply, which is inexhaustible by way of harvesting vibration energy from machines being monitored. This power supply uses a microgenerator to convert vibrational energy into useable electrical energy, and then stores that energy in a supercapacitor so that enough is available for the higher power bursts to measure and transmit condition monitoring data to a basestation.

Condition Monitoring

Plants and refineries monitor both machines and processes to ensure optimum safety, up-time and efficiency. For this article, we will concentrate on the machinery side of things.

Machinery condition monitoring involves measuring the vibrational spectrum of rotating machinery such as pumps, motors and turbines to determine their health. The frequency of vibration is determined by rotational speed and shaft / bearing construction. The amplitude of vibration indicates machine health. For instance, smooth-running machines have low amplitude vibration, while defects in bearing surfaces, unbalanced or misaligned shafts increase the amplitude of vibration. As the problems become more severe, the amplitude increases. Therefore, frequent monitoring of vibration frequency and amplitude reveals problems as they occur to help engineers predict when it is most economical to take equipment offline for maintenance.

Plants will instrument and wire key pieces of machinery - such as turbines, critical high-capacity pumps and motors - when installed. However, it is not cost effective to do this for the “balance of plant,” including the less-critical pumps, motors and compressors that abound in oil refineries, gas plants and mineral processing plants. If one of these less-critical pieces of machinery fails unexpectedly, the plant may incur significant costs in lost production and emergency maintenance. Typically, maintenance engineers monitor “balance of plant” by walking around with a vibration transducer and laptop to periodically inspect equipment, the frequency of which is determined by how critical the equipment is.

It would be far more convenient if a low-cost system consisting of a vibration sensor, micro-controller and radio transmitter was fitted to the balance of plant which could periodically report the vibration spectra to a maintenance basestation. The question then becomes how to power these remote sensors.

Energy Harvesting Provides Perpetual Power Supply

Batteries could power the remote sensors. However, batteries may survive only two to five years in such harsh environments, so in plants with hundreds or thousands of battery-powered wireless sensor nodes, the cost of monitoring, replacing and recycling them is significant.

Given we are monitoring rotating machinery, there is guaranteed to be vibrational energy available. Hence the most natural and attractive solution is to capture this vibrational energy to power the remote condition-monitoring sensors, thereby providing a free, perpetual power supply.

The critical components to this power supply are:

- A PMG17 Microgenerator from UK-based Perpertuum (http://www.perpetuum.co.uk) which can harvest even very low levels of vibrational energy from a smooth-running piece of equipment, and
- A Supercapacitor from Australia-based CAP-XX (http://www.cap-xx.com) which can store this energy and release it in short, high power bursts to read and transmit the condition monitoring data.

Figure 1 shows the block diagram for a condition-monitoring sensor, where the PMG17 is the block labelled Vibration Energy Harvester and the power supply circuit which includes the supercapacitor is the block labelled Power Conditioning and Storage. These will now be described in more detail.

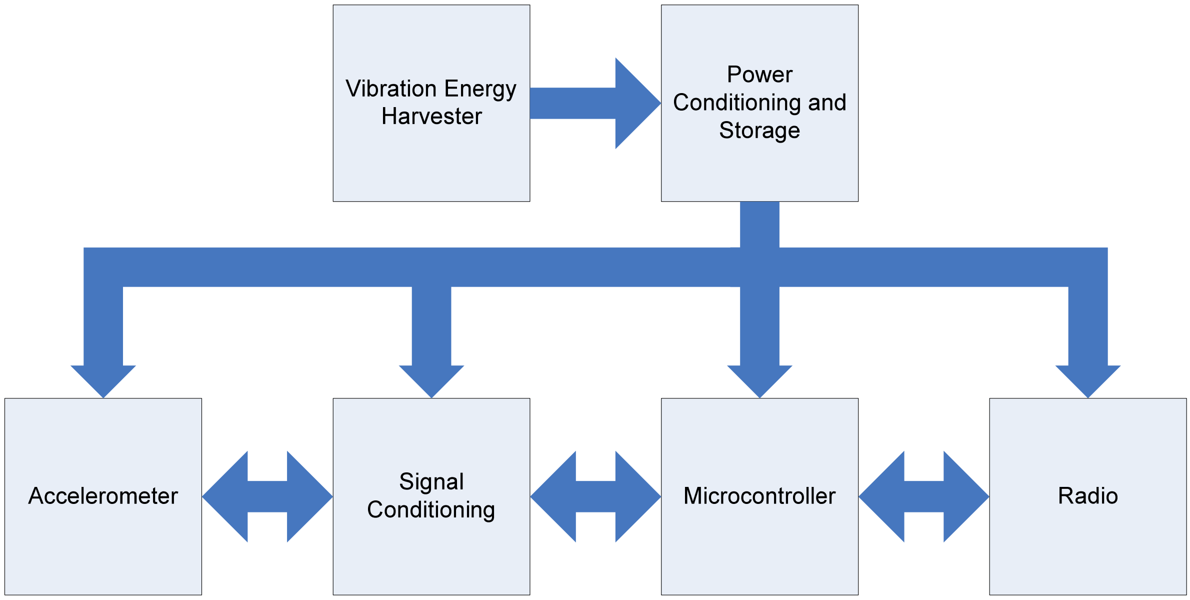


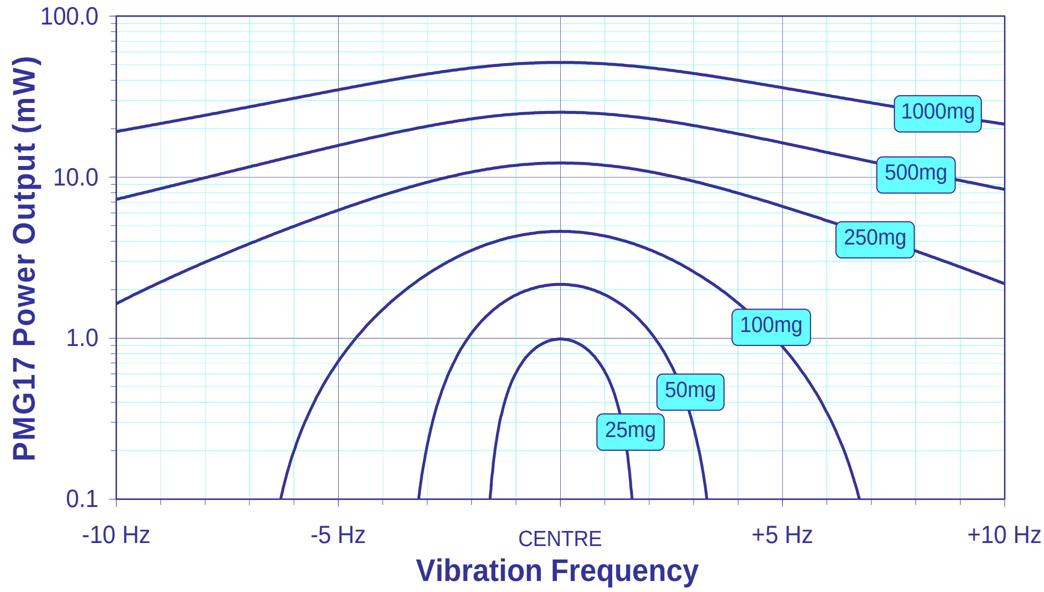
Fig 1: Remote Conditioning Monitoring Sensor Block Diagram

Vibration Energy Harvester

The PMG17 Microgenerator from Perpetuum is the vibration energy harvester used in this unit. An inductive energy harvester with an optimized magnetic circuit coupled to a magnetic resonator designed for AC motors, it harvests the commonly-found "twice the line frequency vibration" so the unit is tuned to 100Hz for a 50Hz AC supply or to 120Hz for a 60Hz AC supply. The PMG17 is highly efficient and with as little as 25mg RMS vibration within a 2Hz bandwidth will produce a minimum power output of 0.5mW.

Figure 2 shows the power output spectra for the PMG17.

Fig 2: **Perpetuum PMG17 Power Output Spectra.**



Interpreting Figure 2, if a unit is tuned to 120Hz to harvest energy from a 60Hz AC motor, then the output power is:

- 1mW if there is 25mg of vibration at 120Hz
- 0.6mW if there is 25mg of vibration at 119Hz
- 1mW if there is 50mg of vibration at 122Hz, etc.

The Microgenerator is a high impedance voltage source. Fig 3 shows the equivalent circuit and the output power as a function of output voltage.

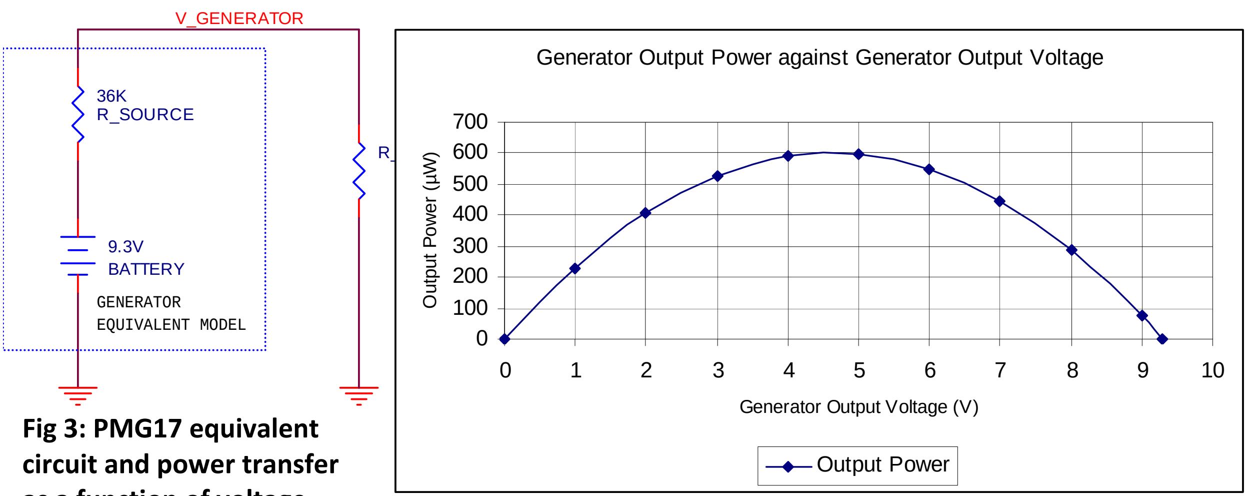


Fig 3: PMG17 equivalent circuit and power transfer as a function of voltage

Fig 3 shows that the power conditioning and storage block should control the current drawn from the microgenerator to maintain its output voltage at approximately 5V to maximize the power transferred from it. This current level will be ~120 micro amps to achieve the 600µW shown in Fig 3.

Power Conditioning and Storage

A dual-cell CAP-XX Supercapacitor, consisting of a pair of HW109 cells, forms the heart of the Power Conditioning and Storage block. It was chosen for the following desirable attributes in this application:

- small and thin, 2 cells, each 28.5mm x 17.0mm x 1.1mm
- high energy storage, 140mF at 5.5V = 2.1J
- high power delivery, only 120mOhms ESR, so max power transfer = 63W
- industrial temperature range from -40°C to +85°C
- can be charged with low current down to 50 micro Amps
- very low leakage current, down to ~3 micro amps with an active balance circuit

Figure 4 shows the power supply circuit. The PMG17 produces AC which is full wave rectified by the diode bridge D1 – D4. To maximize efficiency, the diodes should have low forward voltage and low reverse leakage current. The diodes selected were BAS16 from ON Semiconductor which have good characteristics over the industrial temperature range of -40°C to +85°C. From figure 3 the PMG17 operating voltage should remain in the range of 4V – 6V. There is approximately a 1V drop across the diode bridge, so VCAP will be in the 3V – 5V range. VCAP must be > 3.2V to supply a buck converter with a 3.0V output that drives the data-gathering and transmission circuits. D5 has a reverse voltage of 2V at reverse leakage current of 3 microamps. R2 and D5 ensure that Q1 does not turn on until VCC approaches 5V. As Q1 turns on, VCC drops as charge current flows to the supercapacitor, turning Q1 off again. The PMG17 then charges C9, C11 and C12 until VCC is sufficient so that reverse current flows through D5 and the voltage across R2 reaches VGS of Q1 to turn it on again. With a few 10s of microamps, the combined capacitance of C9, C11, C12 = 66 microF can be charged to 5V in less than 30 seconds. In this manner, R2, D5 and Q1 regulate VCC to ~5V ensuring maximum power transfer from the PMG17 microgenerator to the supercapacitor. At 120 microamps it will take ~1½ hrs to charge the supercapacitor to 4V where it can support a data-gathering and transmit cycle.

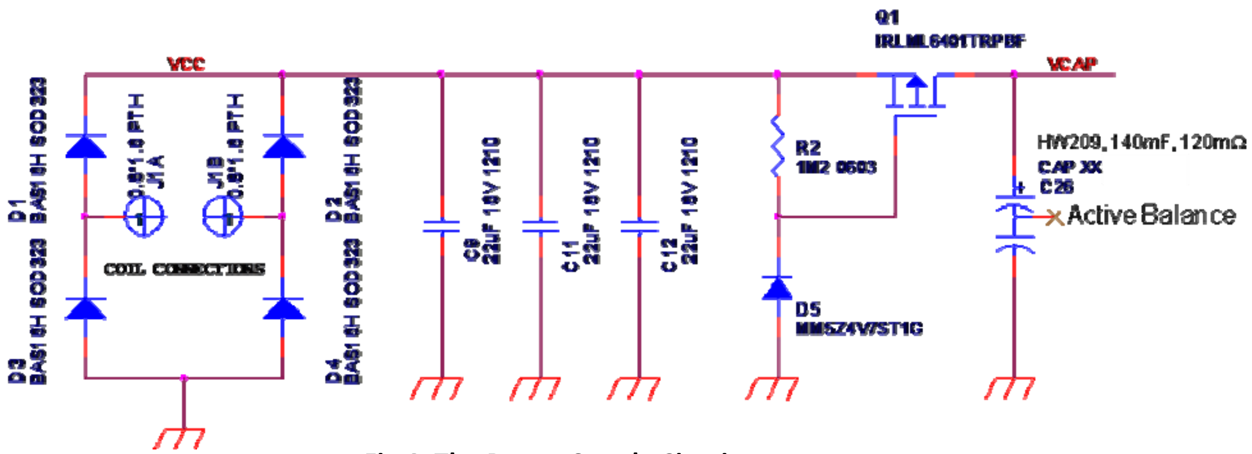


Fig 4: The Power Supply Circuit

A supercapacitor needs a minimum charge current to charge effectively. For very low currents, a discharged supercapacitor does not follow I(t) = CdV(t)/dt. This is because supercapacitor electrodes are porous carbon with ions migrating inside the pores as the supercapacitor takes charge, so some of the current is "diffusion" current, which increases the state of charge of the supercapacitor but does not increase its terminal voltage. At the same time, any impurities will result in electro-chemical reactions which will consume some of the charge, so not all the charge current will increase supercapacitor voltage. This behaviour is illustrated in Fig 5, which shows supercapacitor charging at low values of constant current. Fig 5 shows that charge current should be ≥ 50μA to charge in reasonable time.

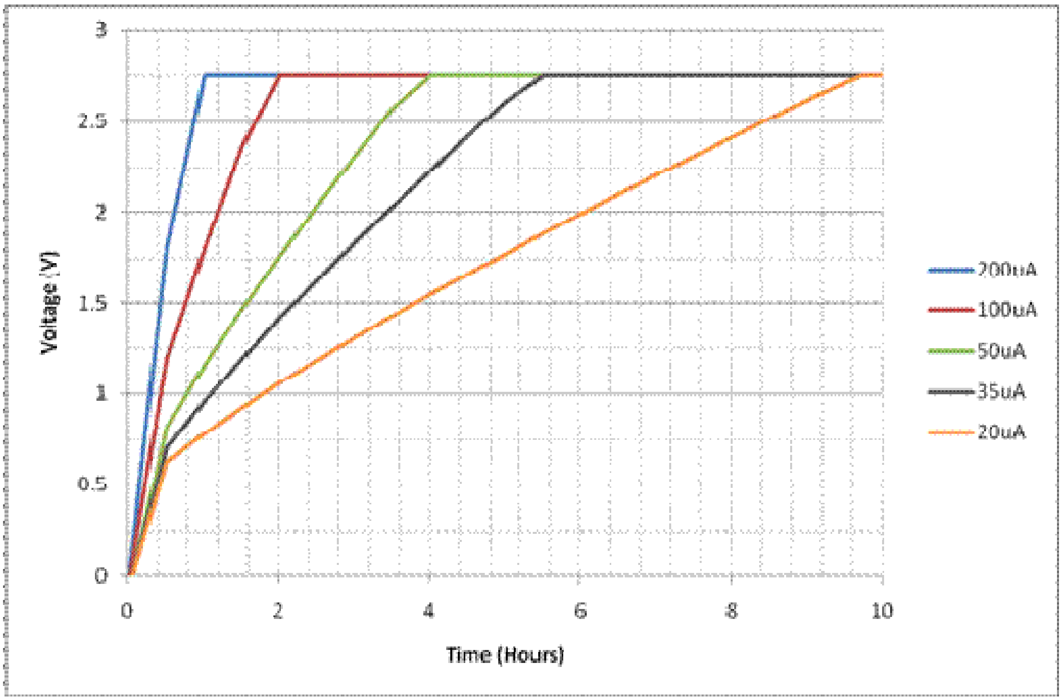


Figure 5: Voltage vs. Time for 200μA, 100μA 50μA, 35μA and 20μA Charge Currents at 25°C

The two supercapacitor cells need to be balanced so that neither goes over voltage. The balancing circuit connects to the node labelled Active Balance in Fig 4. The balancing circuit current + supercapacitor leakage current must be << PMG17 output current ≈ 100uA to 200uA. A high-impedance, low-power operational amplifier, as shown in the balancing circuit of Figure 6, will only draw approximately 3uA, including the supercapacitor leakage current. The operational amplifier chosen needs to be rail-to-rail. It only draws < 1uA supply

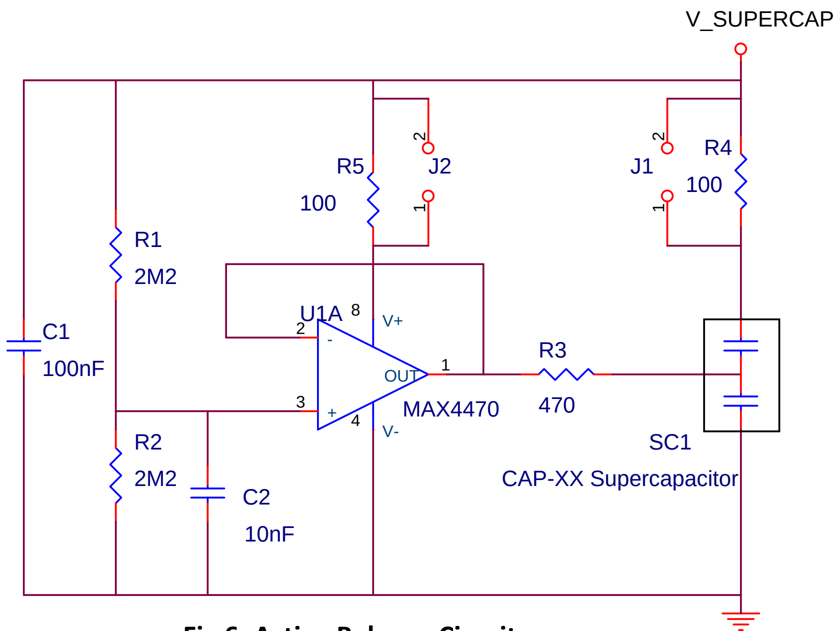


Fig 6: Active Balance Circuit

current and can source or sink up to 11mA to bring cells quickly into balance. Once the supercapacitor is charged, the op amp only supplies or sinks the difference in leakage current between the two supercapacitor cells in series in order to maintain voltage balance.

Determining Supercapacitor Size

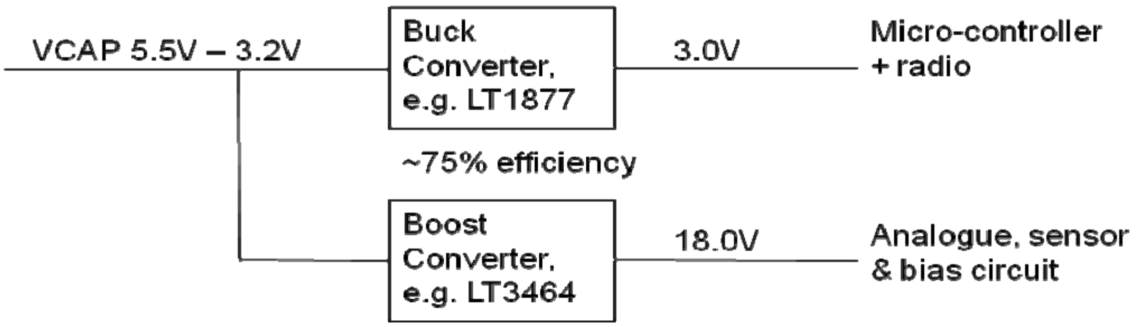


Fig 7: Load supported by the supercapacitor

Fig 7 shows the load supported by the supercapacitor and Table 1 details the energy required. With DC:DC converters that are 75% efficient, the supercapacitor must deliver 83/0.75 = 111mJ. The supercapacitor energy delivered

$= ½ \times C \times (V^2_{initial} – V^2_{final})$

Therefore C required = $2 \times Energy/(V^2_{initial} – V^2_{final})$

= 2 x 111/(52-3.22) = 15mF + 20% tolerance = 18mF

Allow for loss of capacitance due to supercapacitor ageing, so start with double the capacitance, so initial C ≥ 36mF. Select the smallest CAP-XX part that operates over the industrial temperature range, which is the HW209 with C = 140mF and ESR at room temperature range = 120mOhms. ESR at -40°C is approximately 3 x room temperature ESR. Check the suitability of the HW209: peak current = (28mA x 3V/3.2V + 3mA x 18V/3.2V)/0.75 = 58mA, so voltage drop due to ESR at -40°C = 0.36Ohms x 58mA = 21mV << voltage drop from capacitance discharge due to supplying load energy.

Table 1: Energy Budget to determine supercapacitor size

Stage	Voltage (V)	Current (A)	Time (s)	Energy (J)
Sensor & bias circuit	18V	2mA	1.2s	43.2mJ
Analogue	18V	1mA	1.2s	21.6mJ
Microcontroller (sleep)	3V	30uA	1.0s	90uJ
Microcontroller (active)	3V	8mA	0.5s	12mJ
Radio	3V	20mA	0.1s	6.0mJ
Total				82.89mJ

Successful Field Trial

Shell conducted a twelve-month condition-monitoring field trial of this energy-harvesting system in the harsh environment of its Nyhamna gas plant in Norway, which is now operational. The sensors monitored the condition of six rotating motors (rotating equipment is the main culprit in production shutdowns), reporting temperature and overall vibration every five minutes. The trial was a complete success – no failures occurred with the PMG17 or power-conditioning circuitry.

According to the "Successful trial of wireless monitoring at Nyhamna gas plant" article (http://www.cap-xx.com/news/Norwegian_Technology.pdf) in the January 2008 special edition of *Shell EPE Technology Learning Publication*, "The system means that much greater numbers of monitoring points – many in hazardous areas – can be regularly monitored and so help the plant maintenance engineers identify potential system breakdowns in advance." In the same article, Sicco Dwars, Shell Global Solutions R&D Engineer said, "A self-generating power supply is important because batteries have a limited life, particularly when they are required to work outdoors, with temperatures spanning from tropical to arctic conditions."

Fig 8 shows the PMG17 Energy Harvester and Power Conditioning Circuit with CAP-XX supercapacitor. This combination has proven to be an ideal solution to power remote sensors where vibration energy from machinery rotating at AC line frequencies is available.

Fig 8: PMG17 Vibration Energy Harvester and Power Conditioning PCB; CAP-XX Supercapacitor with 25c coin comparing size

About the Author

Pierre Mars is the vice president of applications engineering for Sydney, Australia-based CAP-XX Ltd. (http://www.cap-xx.com). He is a published authority on power management architectures for space-constrained electronics devices, and he jointly holds three patents on supercapacitor applications. Mr. Mars has a B.E. Electrical (1st class hons), M. Eng. Sc. from the University of NSW, Australia, and an MBA from INSEAD, France. He is a member of the IEEE. Mr. Mars can be reached at sales@cap-xx.com, or by calling +61 2 94280107. CAP-XX is located at Units 9 & 10, 12 Mars Rd, Lane Cove, NSW 2066 in Australia.