DOI 10.5162/sensoren2016/2.4.1

Energy Harvesting in Automation

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Abstract

Wireless in automation is seen in a growing number of monitoring applications. These can be primary sensors that monitor a process or secondary sensors which monitor an asset which is part of a process like a pump. This paper shows that energy harvesting is one enabler to leverage the full benefit from wireless installations and discusses the requirements for different applications. At least three power classes spanning the range from a few 100 µW to several 10 mW can be distinguished and various harvesting schemes exist to deliver that power. The cost figure of an energy harvester will be critical to reach mass applications serving the industrial internet of things.

Keywords: Energy harvesting, wireless sensor networks, automation

Introduction

Automation can benefit a lot if wireless sensing systems are used. The full wireless advantage can only be leveraged if also the energy supply is “wireless” and reliable. A key enabler to create truly autonomous wireless sensing devices is energy harvesting.
The key benefits of such energy autonomous systems from an end user perspective are:

1. Greater installation flexibility,
2. reduction of installation and operational cost and
3. easy scalability.

Greater flexibility means that sensing devices can be easily exchanged or moved depending on the current need. Changed process operation, new monitoring or regulatory requirements may require to either add additional sensors or move existing ones.
From an economic perspective wireless installations will reduce a significant amount of engineering, planning and installation efforts. No need for cables eliminates much of the mechanical and electrical preparations needed for traditional wired installations. The cost advantage may vary among different industries, e.g. very remote locations with high associated labor costs will benefit sooner than places where spare infrastructure is available as well as skilled on-site personnel, but the benefit will be always obvious.
If the number of sensing nodes is likely to increase over time scalability matters. Wired systems rely on e.g. electrical installations that are not easy to change or extend. In some cases it will only be costly, in others it may be impossible to add additional sensors due to the missing infrastructure. A wireless infrastructure can be extended more easily and thus quicker and more cost efficient.
Beside all the benefits equal reliability as wired systems needs to be ensured to obtain industrial acceptance.
The power supply is one key aspect of it and shall be the focus of this paper.

Need for Energy Harvesting

Many wireless installations seen today still rely on batteries which can provide all the benefits described above. There is, however, an operational risk associated with the fact that batteries may deplete. There are lots of factors to be considered that may affect the overall energy consumption of a wireless network. If reasonable lifetimes of more than five or even ten years are targeted there are lots of factors that can affect the average power consumption of a network. A few of them are listed in Fig. 1Fig. 1.

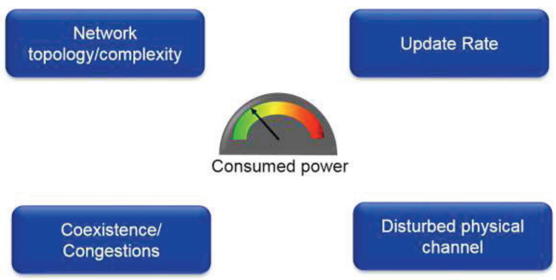

Fig. 1 Factors that impact power consumption of a wireless sensor

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network: Listed are only aspects related to wireless communication

In this figure only communication aspects are listed. There can be even more reasons why power consumption may increase like increased internal sampling rates of a sensor to provide measurement data at higher accuracy or resolution.
Sophisticated wireless communication schemes like, e.g. Wireless Hart or ISA 100 in process automation, are able to ensure network availability but on the cost of consumed power.
The operational risk is that all parameters may change over time. The most prominent ones are added devices, changing environment or increased update rates. It is difficult to estimate future consumption when designing a wireless network, determining a reasonable battery capacity and calculating operational expenditures over the whole lifetime. This can become a hurdle in leveraging the full benefits of a wireless installation because it limits the flexibility, reliability and availability of a wireless sensor network. A non-depleting energy source like energy harvesting can be a means to foster large scale wireless deployments (cf. [1]).

Harvesting Schemes

There is extensive literature on the various harvesting schemes (cf. [2],[3]). In the end the "harvester" does not generate but converts a specific kind of energy into electrical energy. The generic classes are depicted in Fig. 2. There are a number of sub classes and also some exotic ones like bio-energy which are not listed in the figure.

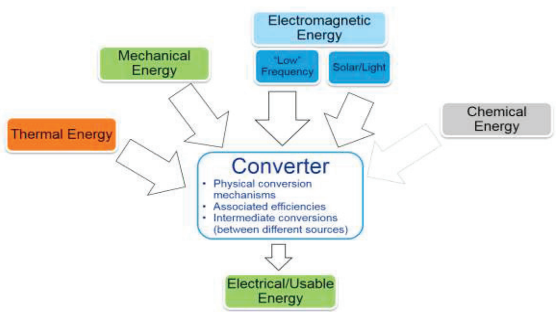

Fig. 2 Rough classification of different energy conversion mechanisms: the converter device is called the energy harvester

It is important to note that the requirements on the converter device are quite high as the lifetime expectation is rather in the order of decades than years. This calls for robust and mature technologies.
Thermal and vibration harvesting shall be taken as an example to discuss the decision criteria for industrial applications.

Thermal harvesting is one of the most applied schemes using thermoelectric generators. The generators themselves are known for several decades and a lot of application experience exist. The ambient conditions that need to be known in order to judge about its feasibility is essentially the temperature differential $\Delta T = T_H - T_K$ between hot source and cold sink. Robustness and ease of application make them favorable even though the thermal conversion efficiency

$$\eta = \eta_{Carnot} \cdot \frac{\sqrt{1+Z\overline{T}}-1}{\sqrt{1+Z\overline{T}}+T_K/T_H} \qquad (1)$$

is inferior compared to other harvesting schemes. Today's commercially available thermoelectric materials (ZT values of approx. 1) reach thermal efficiencies of only a few percent for typical temperature conditions.
The integration of thermoelectric harvesting may still require a decent amount of optimization if space is constraint. This is particularly true for applications where the cold reservoir is ambient air and convective cooling is used and where the volume or size of a heat sink cannot exceed certain dimensions. If the maximum heat sink performance is given, the TEG modules have to be chosen accordingly to achieve maximum performance for a given heat sink. Thermal matching can be studied by simple thermal network models as sketched in Fig. 3.

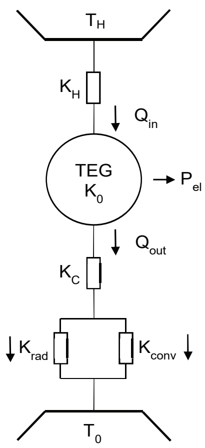

Fig. 3 Simple thermodynamic model with associated heat conductances for a TEG module coupled to hot source at T_H and ambient at T_0: The heat sink is modeled as two parallel conductances (K_{rad} and K_{conv}) describing convective and radiative heat exchange to ambient air.

For a given heat sink thermal conductance the TEG thermal conductance K_0 has to be optimized or chosen to maximize power output.

In Fig. 4 the influence of TEG thermal conductance on the power output is shown.

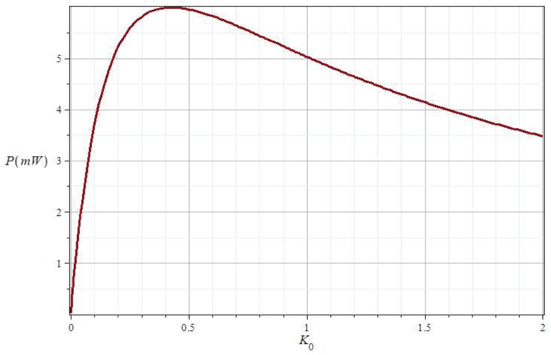

Fig. 4 Influence of thermal TEG conductance K_0 for fixed coupling to hot and could: a given heat sink requires a good thermal matching to achieve maximum power output

In contrast to thermal harvesting kinetic harvesting from vibrations can be much more efficient if resonant systems are used. Electromagnetic, piezoelectric and electrostatic transducers exist. State-of-the-art products are mainly based on harmonic oscillators which means that a compromise has to be done between maximum power extraction (high Q resonator) and frequency bandwidth according to:

$$P_{\max} \cdot \Delta f_{FWHM} = const \quad (2)$$

The maximum power itself depends on quite a lot of parameters like excitation amplitude A, proof mass m, natural frequency ω and maximum input acceleration:

$$P_{\max} \propto A \cdot m \cdot \omega \cdot \ddot{y}_{\max} \quad (3)$$

These facts typically require a detailed on site assessment and make the application more complex. However, if stationary frequency conditions and sufficiently high amplitudes are guaranteed the power output can excel thermal harvesting.

Power Classes

No matter which application is targeted and which harvesting scheme is chosen it has to be admitted that plenty of energy is never available as energy density of ambient sources is always low (cf. [4]).
This fact mandates ultra low power design and power aware operation modes of the sensor nodes.
Tapping into different sources by means of a “multi-harvester” – e.g. thermal and photovoltaic harvesting – is not cost efficient in most circumstances. Modular concepts where a device may be equipped with different power sources and associated power management is typically the more viable option.

Large power output typically corresponds with large system size and high system cost. A rough classification in three power classes is given in Fig. 5:

1. The low power regime comprises devices that need an average power of some few 100 µW. They are typically stand-alone systems and employ hardware as well as communication technologies coming from consumer industries. The device package is not suited for harsh environments and they typically fulfil secondary monitoring tasks. This means they provide auxiliary health information of an asset but no primary process relevant parameters.
2. In the medium power regime devices exist that are either high performance consumer style stand-alone systems or industrial style sensors that are able to deliver process relevant parameters. They can be integrated into distributed control or automation systems and establish robust connectivity by using complex but robust communication schemes.
3. High power devices will most likely show external harvesting adapters due to the large space needed for the harvesting system. The harvesting module has a significant cost impact and is only affordable for sophisticated and costly industrial devices and equipment.

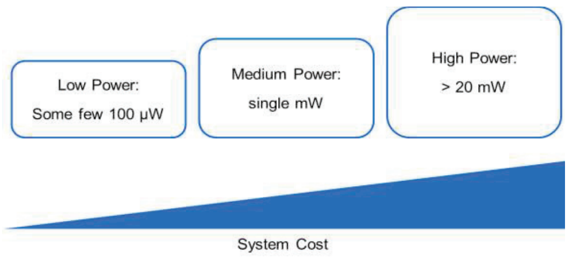

Fig. 5 Classification of harvesting systems according to power output and associated system costs

Conclusions

The benefit of wireless sensing installations can be verified in many scenarios.
It is thus found in several automation applications ranging from process automation via factory automation to home automation and a variety of condition monitoring and asset health monitoring applications.
Cost, robustness and reliability are important aspects to consider in choosing a proper harvesting scheme. They are sometimes even more important than energy conversion efficiency and maximum power output.
Energy harvesting will play a major role as enabler for industrial IoT applications provided that the cost of current solutions will further decrease and become compatible to consumer

like cost figures which are partially adopted by sensing devices already.

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