# Seismic Energy Harvester for High Current Emergency Applications: Gas Valves and Alarms

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***Abstract*— The paper explores if an energy harvester can be used as a sensor for the detection of waves from events such as earthquakes and blasts and at the same time produce high currents for use in an emergency gas valve. A design is proposed for an energy harvester and device that can improve the reliable operation of such valves. The same energy harvester is usable in alarms for seismic events.**

***Keywords*— *energy harvesting; emergency shut-off valve, assisted emergency valve, inductive coil; earthquakes, blasts***

## I. Introduction

Uncontrollable events such as earthquakes or out of control explosions produce large accelerations that can rip off utilities, including gas pipes. Numerous earthquakes in US, Japan, and China lead to major fires due to the braking of gas and liquid fuel pipes during the events [1-4]. Fires started by earthquakes or uncontrolled explosions may produce as much damage as the original events. As a result, safety regulations have been introduced since 2000, first in California (CA) [5], for protecting against the consequences of gas pipe leaks during such events. Safety valves sensitive to large earthquakes (magnitude higher than 5.4 M [5, 6]) are mandatory in CA for all new buildings. The safety valves have to satisfy severe requirements, including operation without any source of energy, guaranteed operation for 30 years without any repair or servicing, and firm closing the gas flow until manual setting on. The interest in emergency gas valves is well illustrated by the number of patents. There are 48 US patents with the combined keywords “gas AND valve AND earthquake”, showing the interest in improved designs for these devices. Representative US patents are [7] and [8]. Other proposals focused on communication networks for the remote control of safety means [9, 10, 11], and on sensors [13, 14].

The structure of mechanical gas valves includes a ball that, under the accelerations due to earthquakes, falls from a support and block the neck of the pipe. The ball may be kicked by a plate or other auxiliary object and pushed out of its support [7, 8]. The use of a plaque to move the ball has the disadvantage of responding preferentially to one direction.

These valves have limits, including the random response (the seismic wave may be on a direction different from the one the ball of the valve is meant to move). A solution is suggested where the seismic or explosion wave is a source of energy for a system that actuates the ball in the valve in a predictable manner, while the system has no source or storage of energy.

## II. Basic Analysis

### A. General Technical Issues

There are two types of emergency applications for energy harvesters: i) the high current, short duration uses; ii) the lower current, longer time uses, which are more common. In the first category we include emergency gas and water valves and high intensity acoustic alarms (blowers); in the second, the lower intensity, post disaster acoustic warnings and lights. The two categories have different requirements for the energy harvester from an earthquake or high energy events. The first category requires high currents during the short hazardous event; the second requires medium currents after the event. The harvested energy is due to the event; its source lasts a few milliseconds to tens of seconds.

The emergency gas valves are based on a metal ball used to obturate the pipe. This study proposes two means for producing the ball displacement. In the first case, an electromechanical actuator is used; in the second, the ball movement is assisted by pushing it out of its normal place by a magnetic field.

### B. Rationale

Earthquake waves are both horizontal and vertical, with the propagation direction of the horizontal waves essentially unknown. Therefore, emergency gas valves [7, 8], having an essentially single direction of freeing the obturating ball from its support, are not optimal. Changing the extant mechanical configuration of the valves has disadvantages. Therefore, another solution has to be devised.

Analysis of the data in the literature indicates that earthquakes, blast due to geotechnical operations and other blasts have different characteristics in the time and frequency domains. Therefore, the operation of gas safety valves designed for earthquake may not respond to events related to blasts. This poses a problem when there is a large probability that the buildings are submitted to blast, such as in war zones.

### C. Suggested solutions description

The solution proposed is to supplement the typical gas safety valves with electric devices that makes them respond to events, while improving the predictability of the operation during earthquakes. Electronic gas valves already exist; they respond to a brusque increase of the gas flow. They are intelligent because they (have to) learn some pattern of gas flow during normal operation. Their operation is less sure, because the gas flow may increase significantly when a larger gas appliance starts operating, while pipe cracks may leak slowly the gas. This makes uncertain the differentiation between the case of small leaks and normal but fast changes in gas flow. Although such valves are accepted by regulations in CA, they are not a true replacement for the mechanical valves. A higher degree of intelligence to make a correct decision on the gas flow, or a radically different solution is needed. For the first case, we suggest that the pattern monitored includes the gas flow, its derivative and the presence of (and level of) vibrations of the ball, or in its support, the last parameter being confirmatory of the external event. The vibration in the support of the ball is easy to detect with an accelerometer; the vibration of the ball on its support is easily detected with proximity sensors.

Another solution is to use an electro-magnetic generator (energy harvesting devices, EHD), with magnets moving due to earthquakes, to generate a current through an actuator that

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kicks the ball out of its support. Such generators can be made to respond to a wide bandwidth covering earthquakes as well and blasts of different origins.

A third solution that is suited specifically to blasts at a distance and sensed only through the atmosphere could be based on a microphone and amplifier. Loubeau et al. [15] have measured with a wideband microphone the blasts. They found that the rise time of the waveform of a close blast, at less than 50 m, is less than 6 μs, with values down to 3 μs. At 100 m, the risetime was 7-16 μs, with no blast having more than 25 μs at distances up to 100 m [15]; this poses a problem for the time the energy is harvested, and to the robustness of the valve under shock [15]. Yet, energy harvesting devices make sense for valves for regions with frequent geotechnical blasts. The paper presents only the outline of the proposed solutions.

## III. Solution for assisting the ball displacement

### *A. Harvester design issues*

Difficulties in design of the system arise from the very different requirements of this type of application, compared with the applications where energy harvesters and related circuitry was designed and commercialized until now. The current, voltage, and power requirements for typical applications of current energy harvesters are to consume very low power, to have negligible standby currents, and to require low voltages from the power supply (see popular references such as [16]. The current, voltage, and power requirements are contradicted by the discussed application, because it is based on an electromagnetic actuator, and that has large currents and possibly considerable voltages (more than 3V) for operation; in addition, no power supply is available between events, because the system cannot include batteries – the battery would anyway dry after a long period, say 10 years unused and not recharged.

The proposed system consists of an electromagnetic energy harvester, a circuit for the control of an actuator, and an electromagnetic actuator aimed to push the ball off its safety position. Many elements of the system are very similar to the ones known in other applications. In the preliminary phases of the design, we used a ball with included magnet and a (stator) coil as the generator, but finally we modified and adopted a solution from the watch industry.

The actuator is a linear solenoid actuator with the rod (armature, plunger) with part of it made of a magnetic material and part of non-magnetic material, for not attracting the ball of the valve. The rod should fully push the ball from its resting position (about 5-10 mm stroke). The required stroke depends on the ball dimension, which depends on the pipe diameter. With actuators having life rating of 5 to 25-million cycles [17], commercial devices can be used. The current required by such an actuator is of the order of 0.1 to 1 A. Commercial actuators have typically 0.5 to 2 A currents, at 3 to 10 V, for a duration of 0.1-0.3 s. The corresponding charge would be $q =< I(t) > \Delta t \approx 10^{-2} \dots 10^{-1}$ C. That, at 10-20 V, would require a capacitor of $10^{-3} \dots 10^{-2}$F $(Q = CV)$. The reader is referred to [17] for examples, but other numerous manufacturers propose similar devices.

### *B. Capacitor use considerations*

The current pulse to the actuator should be delivered at once, with as much as possible available energy. This requires some form of energy accumulation, that is, a capacitor large enough. The requirements for the capacitor are discussed.

A key issue for energy harvesters for this type of application, where the device has to have a guaranteed life time of at least 30 years [6] without being used, or submitted to infrequent use, is the energy storage. Typically, energy storage is performed with capacitors with large values, that is, electrolytic capacitors; these capacitors have a low life time, especially unused. For a 30 years lifespan, the capacitor has to remain operable about 265000 hours under the large thermal fluctuations (-10 to 50ºC in California) and voltage spikes, two stresses known to affect the lifespan [18], [19], [20]; anyway, the lifespan is only 10’000-100’000 hours for film capacitors [19], and the 10’000h for wet electrolytics.

Because electrolytic capacitors and batteries are not acceptable due to their low reliability, a capacitance of at most 100-300 $\mu F$ is feasible at acceptable costs. Capacitors with plastic film or ceramics can be used. Their rated voltage should be at least twice the peak charging voltage (produced under the most brutal accelerations). A rated voltage of 50 V is suitable if the capacitor protection is at 24 V. High reliability capacitors up to 82 $\mu F$ are the TMC series (Nippon Chemi-Con), the AP20 series (AVX-Kyocera), series JSN, film, stacked chip (KEMET Co., 47 – 82 $\mu F$, 63 VDC), etc.

The need of a capacitor voltage protection is explained subsequently. Choosing the capacitor voltage protection is based on the models of capacitors lifetime. Two models are used (see [19, 20]), namely the power low model and the exponential one. According to the first, the life time of the capacitor decreases as $T_{span} = T(U_n) \cdot \left(\frac{U}{U_n}\right)^{-k}$, where $U_n$ is the nominal voltage, $U$ the operation voltage, $T_{span}$ is the average time before failure (lifespan), and $k$ is an empirical constant; Gallay [20] suggests $k = 3 \cdots 5$. The exponential model is $T_{span}(U) = T(U_n) \cdot \exp\left(-\alpha \frac{U-U_n}{U_n}\right)$ with $\alpha$ an empirical constant. These laws (applied by Gallay to Vishay capacitors, [20]) show that by using a capacitor at $U_n/2$ increases its lifetime 5- to 10-fold.

On the other hand, the temperature $t^{o}$ has an exponential detrimental effect on the lifetime, with $T_{span}(t^{o}) = T(t_n) \cdot \exp\left(-\frac{E}{k_B} \cdot \left(\frac{1}{t^{o}} - \frac{1}{t_n^{o}}\right)\right)$, where $t_n^{o}$ is the nominal temperature, $k_B$ is the Boltzmann constant, and $E$ is an (empirical) activation energy [20]. Gallay [20] shows that an increase from 40ºC to 70ºC reduces the lifetime of capacitors about 7 times. Because one can expect that during summers the temperature of the valve and of the capacitor can frequently be 70ºC, a compensating factor should be used by under-rating the operation voltage by half. To ensure this condition and the randomly varying voltage from the generator, in the proposed schematic the capacitor is protected by a bidirectional voltage limiter. [19] determines that at “*0.6 V x UNDC, the capacitor withstands 1’000’000 hours of operation.*” This justifies the use a voltage limiter in the circuitry, although this leads to energy loss. Finally, another important parameter for the storage capacitor is its dV/dt rating, which should be high in this application where one is interested to waste the minimal power over the parasitic resistances in series with the circuit.

### *C. Assisting the ball displacement*

Two solutions for assisting the ball displacement toward the safety position are sketched in Fig. 1. The first solution involves an electromagnet attracting the ball upwards and sidewards, for helping removing the ball from its resting position. The second is a linear actuator that actively pushes the ball from its equilibrium position.

The generator has to produce enough power as necessary for the actuator. This can be achieved only with a large swinging mass (not shown in Fig. 1) of the order of 100 g, with the disc-sector (half-moon or similar) swinging piece with a radius of a few cm. The swinging mass is similar to those for the watch mechanisms, see [21], [22], but larger. A gear for increasing the rotation speed is needed for a good efficiency. The gear has to be self-lubricated because no grease can be expected to work well for 30 years in a wide range of temperatures.

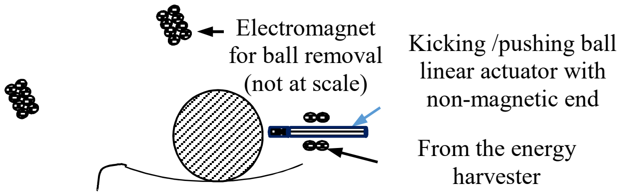


Fig. 1. Sketch of the two solutions discussed.

A small a.c. generator produces the power for activating the actuator. A direct source of knowledge comes from the automatic power generating system watches [21]. The clock generators use a ‘half-moon’ (semi-circular or sectorial) weight rotating in the plane of the watch and a mechanical gear to increase the rotation speed about 100-fold. The use of a high frequency rotation of the magnet improves the energy conversion efficiency and produce larger voltages, according to $u_{emf} = -d\Phi/dt$ for a turn of the coil, $\Phi = \int_{A\ coil} BdA$ .

## D. The generator

A first version of generator was imagined as in Fig. 2 and used a second ball with a magnet included, oscillating due to the earthquakes over a set of coils. This solution was found later to be somewhat similar to the “goblet” generator presented in [23]. When the two balls have identical mechanical properties, they will move in the same way, that is in phase, under the earthquake shaking. However, the loss of energy through the transfer from mechanical to electrical will slow and diphase the movement of the ball in the harvester. Yet, the two balls will not be in antiphase. This variant was abandoned because the efficiency is low and the generated current insufficient for the actuator operation; yet, more studies could lead to an improved version. Further studies of this solution are justified by advantages including the twining of the two balls, which may allow the synchronization of the actuator operation with the movement of the ball that is aimed to obstruct the pipe.

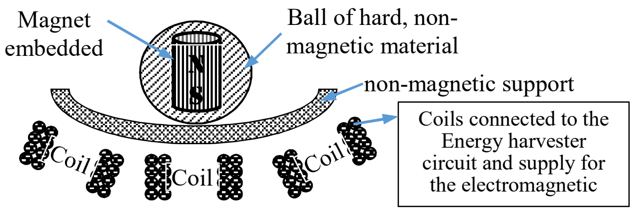


Fig. 2. Schematics of a first version of free-ball generator.

There are some uncertainties in the operation of the harvester, because the resonances of the case of the sensor and of the pipes supporting it are essential in determining the response to explosions and earthquakes. Their resonances depend on the actual geometrical dimensions, their stiffness, and on the geometry and rigidity supports of the pipes. Because of the variability of these parameters for the various implementations, these resonances are difficult to estimate.

## E. The energy harvester circuit

The generator (even a d.c. one) cannot directly supply the linear solenoid actuator because the random swinging of the mass under earthquake conditions. A rectifier is needed as an intermediate stage.

The harvester includes two generators having the swing (inertial) masses in different planes, two rectifiers, the energy storage capacitor, a voltage limiter on the capacitor, the electronic switch with a threshold detector closing the circuit when a certain voltage is reached on the capacitor, and the actuator circuit with its protection. The capacitor reduces the effect of rapid fluctuations of the voltage from the rectifier on the threshold of activation of the actuator. C1 is the storage of the energy. ZD1 protects the capacitor; in combination with R2 and ZD2 it also limits $V_{GS}$. ZD2 and R2 determine the voltage threshold for delivering current to the actuator, when enough charge is stored on C1. When C1 is well charged, there is enough voltage on R2 and Q opens. A third diode (DZ3, not figured) may be used to prevent a too large voltage on the gate.

The frequency of the earthquake waves is between 0.1 Hz and 10 Hz; the inertial swinging mass is expected to have (random) movements with frequencies in this range. For reducing vibrations of the actuator pushing rod, the current through the actuator has to be filtered; C2 plays this role.

Using two semi-circular weights, one in the horizontal plane and one vertical, would ensure that whatever the seismic wave type is, the necessary energy is generated for the assisted emergency ball valve. The use of two independent swinging masses requires two rectifiers, connected such that no one injects current into the other (hence the two extra diodes).

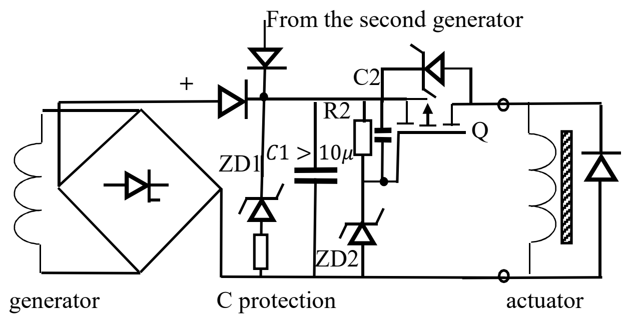


Fig. 3. Basic circuit for the energy harvester and ball control of the emergency valve.

The scheme in Fig. 3 can easily be complemented by a microcontroller for monitoring the state of the storage capacitor and for driving the MOS switch, but that would require, for reliable operation of the microcontroller, the use of large capacitors in its power supply, which would increase the cost and reduce the overall reliability.

## F. Application to earthquake alarms

When earthquakes strike at night, people may waste precious seconds before awaking and realizing the situation. A strong sound alarm that goes off in the first seconds in the bedrooms may save lives. The alarm could be powered by the energy harvester in Fig. 3; an electric siren, signal horn, or electric bell at 0.5-1 A matches well this application.

## IV. Discussion and Conclusions

The suggested designs revolve around two requirements: high reliability and low cost and therefore low circuit complexity. Instead of the threshold circuit based on Zener diode - resistance in Fig. 3, one could use a capacitance voltage divisor that is also detecting large accelerations. One of the capacitors in this version of the suggested circuit is a plate or interdigital capacitor (see formula governing the change in capacitance and constructive versions in [24]) with a fixed plate and a second plate free to oscillate. Due to large oscillations, the capacitance varies and brings the gate of the MOS transistor at the opening voltage. (A similar principle of variable capacitor is used in MEMS accelerometers.) However, this solution determines an intermittent operation of the MOS and might make ineffective the actuator operation; this solution was not checked under large vibrations.

The proposed system could be complemented with a second control system based on a microcontroller that starts operating when enough energy is available. However, this system should act only as a reserve that takes over the main system when enough energy is produced such that the operation of the safer, basic system presented is not hampered. It is preferable for safety reasons, in our opinion, to use a second safety valve, based on the principle of excess flow sensing (see [6] for a description); the two valves can act independently and can be connected in series.

Very large accelerations and oscillations of the swinging mass can destroy the mechanism of the energy harvester. A solution can be the use of damping materials with electro-rheological fluids, see [25].

Concluding, the article presented the outlines for the design of a reliable actuating system for emergency gas valves; the system, while apparently simple, rises several technical difficulties, including the mandatory lack of battery, the high current required by the actuator, and the high reliability of the capacitor(s) used. In fact, the simplicity of the circuit is its main asset and was the goal of the design.

The safety valve is not a definitive solution because internal leaks due to ruptures of the internal pipes may occur. After restoring the flow through a safety valve, every room in the buildings have to be checked for potential leaks. An alternative is to have gas sensors in every room, where the sensors send the information to the main pipe valve, which establishes the flow after some minimal time passed, to allow gas accumulations from smaller leaks.

**N.B.** This research and the paper presentation was not supported by any institution. Patent pending.

## Acknowledgments

The author thanks the reviewers for helpful comments.

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