SMART MATERIAL

CL-54
Energy Harvesting Circuit
User Manual

Version 2.0

CONTENTS

This document is for the instructional use of the CL-54 piezo energy harvesting circuit. Please read carefully before using the equipment.

1. OVERVIEW

The CL-54 is an energy harvesting electronic circuit board. The circuit board accepts the alternate current (AC) output of one or more Piezo Electric Harvesters devices (PEH) as input and generates a 3.3V stabilized, direct current (DC) as output.

A Piezo Energy Harvester (PEH) transforms mechanical or kinetic energy into electric energy in the form of an electric charge; or, if its output is connected to any type of electric impedance, as an electric current. A Piezo Electric Harvester can be best understood as an alternating current source with a capacitor and resistor connected in parallel.

The CL-54 was designed to aid in the testing and development of various piezo electric harvesting applications, which are used for the autonomous operation of µProcessors, sensors, and/or IoT systems. With its various features it is also very well-suited for general educational purposes and experiments.
The CL-54 was specifically designed to work with piezo electric energy harvester systems based on the P2 type MacroFiberComposite™. The device will also work with most other types and brands of d_{31}-mode piezo electric energy harvesters.

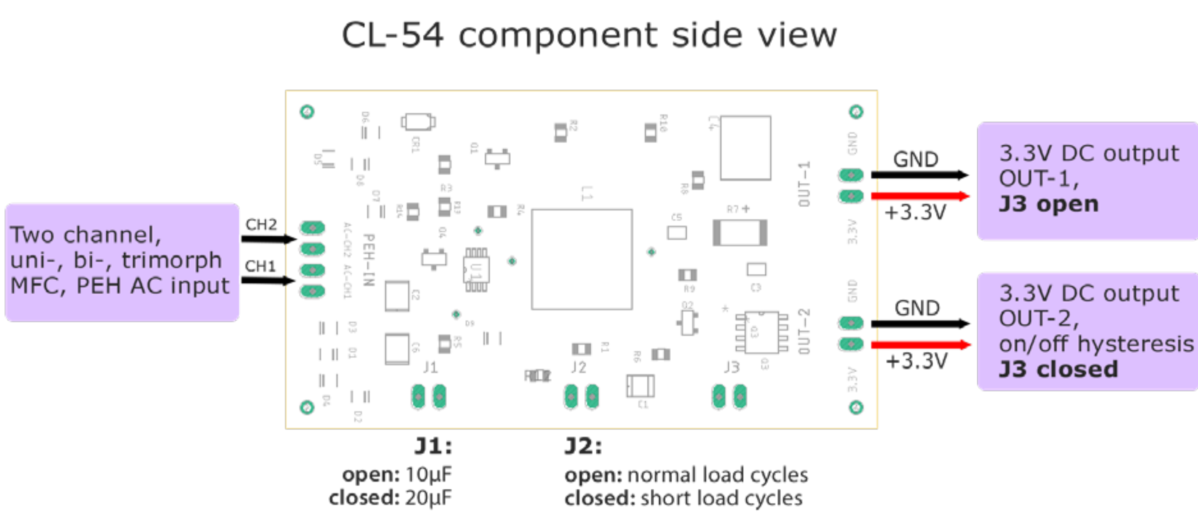

Fig 1: In- and Outputs, Jumper configuration CL-54

The CL-54's basic functions are:

- to rectify the AC current input from one or two PEHs with bridge rectifiers,
- supporting uni-morph, bi-morph or tri-morph PEH setups,
- to store the harvested electric energy in a capacitor of 10µF or 20µF, selectable with jumper **J1**,
- generating with open jumper **J3** a stabilized 3.3V DC voltage on output **OUT-1**,
- to store energy retrieved from the PEH in a 1mF (1000µF) capacitor with jumper **J3** closed, which can be retrieved in high current, electric power bursts on output **OUT-2**,
- to support different PEH load cycles periods, selectable with jumper **J2**.

2. WHAT COMES WITH THE CL-54?

The CL-54 package contains the following items:

1. The CL-54 printed circuit board (PCB).
2. Three jumpers to close jumper positions **J1, J2, J3**.

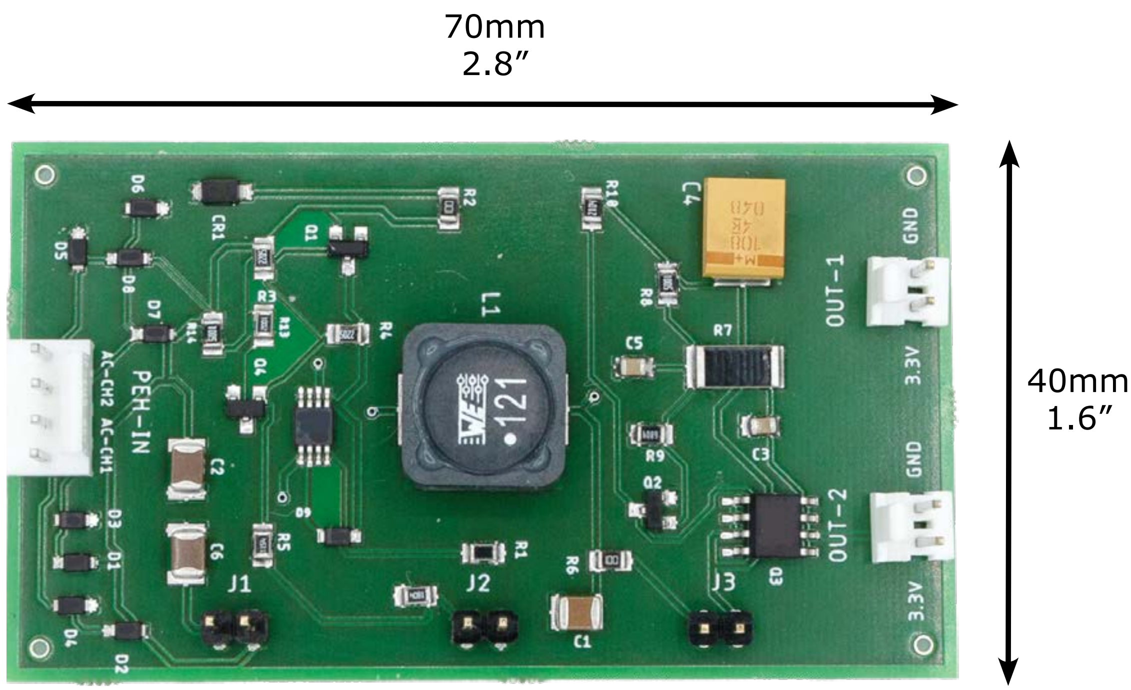

Fig 2: CL-51 component side

3. SPECIFICATIONS

3.1 GENERAL SPECIFICATIONS

Operating Conditions	Ambient Temperature -25°C to 85°C (13°F - 185°F)
	Relative Humidity up to 85%, noncondensing
Mechanical	PCB dimensions: W x L x H = 40mm x 70mm x 14mm. 1.8" x 2.8" x 0.55"
	PCB weight approx. 25 g
Input Connectors	***PEH-IN,*** piezo electric harvester inputs, two PEH channels with two wires each, AC no polarity preference
Output Connectors	***OUT-1*** and ***OUT-2,*** stabilized DC voltage outputs, GND (Ground), +3.3V

3.2 ABSOLUTE MAXIMUM RATINGS

Max. Input Voltage	± 95V AC
Max. Input Current	200mA
Max. Output Current	50mA on ***OUT-1***, 800mA on ***OUT-2***

3.3 ELECTRICAL AND PERFORMANCE CHARACTERISTICS

Output Voltage	3.3V DC ± 0.1% line regulation
Typical Output Power	0 - 148mW @ 3.3V on output ***OUT-1,*** 0 - 2.7W @ 3.3V on output ***OUT-2,*** depending on the available, harvested input energy
Typical Efficiency **J2** *open*	81% at 1mA output current 87% at maximum output current
Typical Efficiency **J2** *closed*	90% at 1mA output current 92% at maximum output current

<table>
<tr><td rowspan="3">Min. input energy for output
OUT-1 to activate after full discharge
J3 *open*</td><td></td><td>**J2** - closed</td><td>**J2** - open</td></tr>
<tr><td>**J1** - open</td><td>~2.9mJ</td><td>~0.4mJ</td></tr>
<tr><td>**J1** - closed</td><td>~5.8mJ</td><td>~0.8mJ</td></tr>
<tr><td rowspan="3">Min. input energy for output
OUT-1 to activate,
continous operation > 0.3Hz
J3 *open*</td><td></td><td>**J2** - closed</td><td>**J2** - open</td></tr>
<tr><td>**J1** - open</td><td>~2mJ</td><td>~0.3mJ</td></tr>
<tr><td>**J1** - closed</td><td>~4mJ</td><td>~0.6mJ</td></tr>
<tr><td rowspan="3">Min. usable energy for output
OUT-1
J3 *open*</td><td></td><td>**J2** - closed</td><td>**J2** - open</td></tr>
<tr><td>**J1** - open</td><td>~1.7mJ</td><td>~0.28mJ</td></tr>
<tr><td>**J1** - closed</td><td>~3.8mJ</td><td>~0.57mJ</td></tr>
<tr><td>Min. input energy for output
OUT-2 to activate
J3 *closed*</td><td colspan="3">~6.5mJ</td></tr>
<tr><td>Min. usable energy
output ***OUT-2***
J3 *closed*</td><td colspan="3">> 2.2mJ, each on-cycle</td></tr>
<tr><td>Input voltage clamp</td><td colspan="3">43V (DC side of the bridge rectifier)</td></tr>
<tr><td>Min. input current</td><td colspan="3">0.9μA</td></tr>
<tr><td>Max. usable input current</td><td colspan="3">57mA</td></tr>
</table>

1mJ = 1mWs

4. OPERATIONS

4.1 CL-54 INPUTS

The CL-54 features two PEH A/C inputs, channel 1 and channel 2, which allow harvesting energy of two independent uni-morph PEHs, a bi-morph or a tri-morph PEH. If only one input channel is required, the PEH can be connected to either input channel, with the channel not used left open.
The output voltage of a PEH is a function of the electric current that the PEH is generating, the PEH internal impedance, and the impedance connected to the PEH output, i.e., the CL-54.

The CL-54 has a variable input impedance, which is a function of the

- internal charge level of the on-board capacitors,
- the state of the onboard control electronics,
- closed or open jumpers J1, J2, J3,
- the load connected to the output of the CL-54.

Due to the variable input impedance of the CL-54, the voltage measured at the ***PEH-IN*** terminals will vary during energy harvesting operation. When the CL-54 is connected to the PEH, the voltage oscillation will typically measure between 0V to ±21V (**J2** closed) or 0V to ±9V (**J2** open). The voltage can be in a no-load condition (no load is connected to either of the two outputs) as high as ±43V.
The CL-54 will use a certain amount of the harvested energy for performing its functions. The amount used is typically between 15-30% of the total harvested energy.

4.2 JUMPER J1 AND J2 - PEH CHARGE RETRIEVAL SETTINGS

Jumper **J1** is by default open.
If Jumper **J1** is closed, it changes the input capacitance from 10µF (**J1** open) to 20µF. This will typically increase the time when the output is activated (based on a same PEH energy input) but also increases the time the output will stay on (based on the same load connected to the output) .

Jumper **J2** is by default closed.
If Jumper J2 is open, the threshold for the minimum energy required to activate the DC voltage is lowered by an approx. factor of 7. The values are listed in the table under **3.3**.

4.3 DC OUTPUT MODES

The CL-54 has two 3.3V DC outputs, labeled ***Out-1*** and ***Out-2***. Jumper **J3** selects which output is active. Jumper J3 is by default open and ***Out-1*** activated.

4.3.1 STANDARD MODE: JUMPER J3 OPEN (DEFAULT)

This is the standard energy harvesting mode and the output ***OUT-1*** is active. This output has a 20μF capacitor as output buffer. The ouput activates as soon as the CL-54 has collected enough energy from the PEH. The CL-54 output ***OUT-1*** has three typical operational states, depending on the harvested energy generated by the PEH(s). If the CL-54 has been disconnected from an energy source for several minutes, it requires an initial amount of energy before entering into states 2. or 3. (see table under 3.3).

1. The CL-54 is not activating ***OUT-1***

   The PEH current is less than 900nA; the amount of harvested energy is too low. The CL-54 will stay in the off mode. ***DC-OUT*** will remain at 0V.

   TIP: Make sure jumper J1 is open. A simple way to troubleshoot this condition is to measure the input voltage of the PEH at the ***PEH-IN*** *terminals with a high impedance probe (>50MOhm). If the voltage is not reaching ~23V (jumper J2 open) or ~10V (jumper J2 closed) at <u>any time</u>, the supplied current or harvested energy is too low. Increase the strain on the PEH.*

2. The CL-54 is switching ***OUT-1*** on intermittently

   The energy harvested by the PEH is <u>less</u> than the energy required for the load, connected to ***OUT-1***, to operate continuously. This is one of the common operational modes of the CL-54. The CL-54 collects harvested energy from the PEH in the on-board capacitors over time. After the collected energy reaches the energy threshold listed under 3.3 (minimum input energies for the selected jumper **J1** and **J2** combination), the CL-54 activates ***OUT-1*** and provides a stabilized DC output voltage of 3.3V.

   Fig. 3 shows a typical waveform for intermittent ***OUT-1*** cycles.

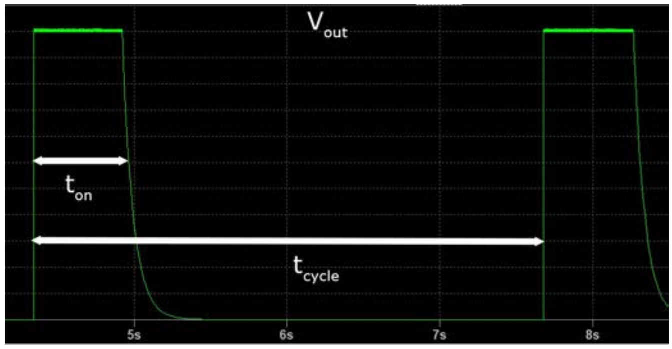

Fig 3: CL54 intermittent DC-OUT mode

The ***OUT-1*** on-time $\mathbf{t_{on}}$ is the rate to discharge the collected energy into the load, until the stored and continuously collected energy reaches a low threshold. The cycle time $\mathbf{t_{cycle}}$ minus $\mathbf{t_{on}}$ is the time $\mathbf{t_{charge}}$ required to reach the stored energy again, based on table **3.3** (Minimum input energies for the selected jumper **J1** and **J2** combination, continuous operation).

Choosing different jumper combinations for **J1** and **J2** will change $\mathbf{t_{cycle}}$, $\mathbf{t_{on}}$ and $\mathbf{t_{charge}}$ **.**
In general, considering the same PEH setup,

- J1-closed will increase $\mathbf{t_{on}}$ and $\mathbf{t_{charge}}$,
- J2-closed will lower the minimum energy input threshold and decrease $\mathbf{t_{on}}$ and $\mathbf{t_{charge}}$.

3. The CL-54 keeps the ***OUT-1*** on continuously

   The energy harvested by the PEH is higher than the energy required for the load, connected to ***OUT-1***, so it will operate continuously. After the initial charge-up period, the CL-54 provides a stabilized, continuous DC output voltage of 3.3V.

4.3.2 HIGH POWER STORAGE MODE: JUMPER J3 CLOSED

In this mode the ***OUT-2*** is active. The output has an additional 1mF (1000μF) capacitor added to the 20μF output capacitor to store a larger amount of energy at 3.3V, generated by the PEH(s). This output is especially designed for providing burst power rates for μProcessors, sensors, and IoT systems. These devices often need a high current supply of 5-40mA in bursts for 10-30ms to boot and send data packets via Bluetooth and other wireless protocols.

The output ***OUT-2*** has equal states **1.** through **3.**, as listed in the prior chapter **4.3.1 STANDARD MODE**.

The important differences are the higher minimum energy required to activate the output, as listed in the table under **3.3**, and that the ***OUT-2*** output is a switched output.
The output switch works with a hysteresis of 3.28V to 2.5V, switching the output on at 3.28V and switching off at 2.5V. Typically electronics requiring 3.3V will work within this voltage range. The output is capable of discharging the 1mF capacitor at rates of up to 800mA.
Switching off the discharge current of the 1mF capacitor at 2.5V preserves the remaining charge of the 1mF capacitor. Thus the PEH simply has to "fill up" the energy required to charge the capacitor from 2.5V to 3.28V, which amounts to ~2.2mJ. The minimum energy available on the output during a discharge cycle is therefore > 2.2mJ, increased by additional energy retrieved from the PEH during the discharge cycle.
Fig. 4 shows a typical waveform for intermittent ***OUT-2*** cycles.

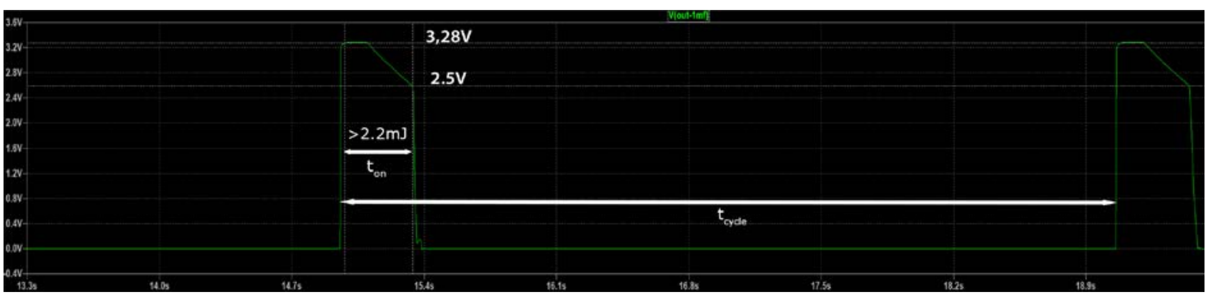

Fig 4: OUT-2 intermittent output mode

Due to the switched output, the **J1** and **J2** selection will not change $\mathbf{t_{on}}$ in the same way as outlined for the Standard Mode in **4.3.1**. The ***OUT-2*** will always have a minimum time $\mathbf{t_{on}}$.
The minimum time $\mathbf{t_{on}}$ can be calculated by dividing the minimum energy, i.e. 2.2mJ = 2.2mWs with the power P=U*I, where I is the current which the connected electronic circuits require to work and U is the average voltage during $\mathbf{t_{on}}$. $\mathbf{t_{on}}$ is extended, if during the discharge cycle additional energy becomes available from the PEH.

4.4 NO-LOAD AND PEH SETUP CONDITIONS

No-load or load setups with an energy input from the PEH that exceeds the load requirements might trigger the internal circuit protection.
This protects the circuit against over-voltages in excess of 43V.

The circuit is only triggered after the stored energy reaches input values of more than ~10mJ and temporarily short-circuits any excess energy. It will not disable standard operation.

Caution should also be exercised when connecting a PEH to the CL-54. Especially when the PEH is actively harvesting energy, or, is not completely discharged, it might have a high voltage charge at its output connections. As outlined before, a PEH is a capacitor and can generate voltages in excess of ± 95V in an open circuit condition. If connected to the CL-54, such high voltage charges can cause transient voltage peaks, which can damage the CL-54.

5. ENERGY VS. POWER

Electrical energy and electrical power are often used in a way suggesting that they are interchangeable. ***They are not!***
Energy and Power are closely related, but they are not the same. This is an important fact to understand if designing energy harvesting applications.

Energy is defined as the capacity to do ***work***. Work can be in the form of kinetic energy, potential energy and thermal energy. It is also correct to say, that if you are doing work to an object, you give the object energy. Furthermore, you can add energy to an object by transferring heat. This is the first law of thermodynamics: The total energy of a system can be increased by doing work on it or by adding heat.

Energy is measured in **Joule, J** (SI unit). One Joule is equivalent to 1 Nm (one Newton times one meter) and 1 Ws (one Watt times one second). Examples for how to calculate energy:

$$\boldsymbol{Kinetic\ Energy} = \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{mv^2}\ (m = mass, v = velocity)$$

$$\boldsymbol{Potential\ Energy} = \boldsymbol{mgh}\ (m = mass, g = gravity, h = height)$$

One of the energy calculations which is used for the CL-54, is the stored energy in a capacitor:

$$\boldsymbol{Energy\ Capacitor} = \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{CU^2}\ (C = Capacitance, U = Voltage$$

Power is the ***rate*** of doing work or the ***rate*** at which energy is used, produced, or transferred.

$$\boldsymbol{Power} = \frac{\boldsymbol{Energy\ Used}}{\boldsymbol{Time\ Taken}}$$

The unit of power is the unit for energy divided by the unit for time. In SI units this is Joule divided by seconds, which is given the name **Watt**, **W**.

Many people are familiar with the electrical energy amount of a kWh (kilo Watt hour). It is important to understand that you spend the same amount of energy if you are using 1kW for one hour or if you are using 1W for one thousand hours.
Or, it is the same amount of potential energy as when a crane is lifting a 1ton stone block 20m up in 1min or 1hour. But the required power for the motor of the crane is higher if you lift the block in 1min instead of 1hour because the time interval is different.

How does this relate to energy harvesting circuits?
As mentioned in the overview, the CL-54 stores the harvested energy in a capacitor. A capacitor can discharge stored energy in a very short time. In comparison, a battery can typically store a larger amount of energy than a capacitor, but can discharge it only during a much longer period of time.

In combination with a piezo electric harvester (PEH), a piezo electric harvesting circuit can be seen as a power booster, changing the time the collected and stored amount of energy from a PEH is supplied to a consuming circuit (not an energy booster, which is not possible in this universe!). Since the energy amount has to remain the same, the energy harvesting circuit will distribute the energy in periods of On-cycles with higher power discharge ratings and periods of Off-cycles, if the energy supplied by the PEH is less than the energy required by the consuming circuit for the same period of time.

6. FURTHER RESOURCES

Follow our popular in-depth tutorials on our YouTube channel **SmartMaterialCorp.**

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