

## **BALLISTIC IMPACT DETECTOR**

### **TECHNICAL FIELD**

**[0001]** This disclosure relates to detection of physical attacks on power grid infrastructure, including detection of ballistic impacts on transformers and other vulnerable equipment.

### **BACKGROUND**

**[0002]** The number of attacks on electrical distribution critical infrastructure and transformers in particular have steadily increased over recent years. Just piercing the casing of an oil-cooled transformer casing does not usually cause the transformer to explode; rather, the loss of the transformer's protective dielectric (oil) can eventually cause the coils of an energized transformer to overheat and eventually lead to combustion of the remaining oil. Ignition of the oil rapidly leads to overpressure followed by explosion and in many cases complete destruction of the transformer. If a transformer does explode, for example, the explosion may damage other transformers in the area such that they, too, leak and eventually explode, potentially causing a chain reaction of extensive damage.

**[0003]** Thus, there is typically a window of time after a bullet has pierced a transformer in which the transformer could be safely de-energized and thus avoid an explosion or other catastrophic event (or chain of catastrophic events). Once de-energized, the transformer casing could be repaired and refilled with oil, or the transformer can be replaced entirely.

**[0004]** Presently, no viable method of interdiction exists except for physical barriers which are limited in protection ability and are extremely expensive to deploy. Likewise, no viable method of detection of an imminent threat from an assailant using a high-powered rifle exists due to the limitations of conventional surveillance methods and the ease with which said assailants may remain hidden from view by proximate vegetation and terrain.

**[0005]** For example, one conventional approach to detect gunfire is to use one or more microphones to try to identify the sounds of gunshots in the vicinity of a power substation, but even presuming that such methods correctly distinguish between a gunshot and other percussive sounds, such methods don't provide an accurate location of

the source of the sound. Another conventional approach is to use triangulation or trilateration based on detection of a sound by multiple microphones. While such methods may be able to identify an estimated location of a shooter, they cannot distinguish between a hunter shooting away from the substation and a domestic terrorist or vandal shooting towards the substation.

**[0006]** Most importantly, even presuming that these conventional methods can detect the location of shooter and direction of the shots, they cannot indicate with certainty that a particular piece of equipment has or has not been hit by a projectile. Since many portions of a power grid are located away from population areas, and in some cases may be in remote areas or even wilderness areas, the power utility operator may be left with a difficult choice each time a gunshot has been detected near power grid equipment: send an inspector to a substation or other equipment site every time conventional systems detect a gunshot in the vicinity, to determine whether or not any of the equipment has been struck by a bullet, or take no action and hope to be able to determine that some equipment has been struck by a bullet (e.g., by detecting a degradation in performance) in time to de-energize the equipment before it explodes.

**[0007]** Thus, there is a need for techniques to accurately and cheaply detect when transformers or other types of equipment have been hit with a high-power projectile and to quickly notify the operator of that equipment.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0008]** Embodiments of the subject matter described herein will now be explained with reference to the accompanying drawings, wherein the like reference numerals represent like parts, of which:

**[0009]** FIG. 1 shows an exemplary apparatus for detecting ballistic impacts, according to embodiments of the disclosure;

**[0010]** FIG. 2 is a flow chart illustrating an exemplary method for detecting ballistic impacts, according to embodiments of the disclosure;

**[0011]** FIG. 3A is a graph showing an impact waveform for a low-energy impact, e.g., a hammer strike; and

**[0012]** FIG. 3B is a graph showing an impact waveform for a high-energy impact, e.g., a bullet strike.

## DETAILED DESCRIPTION

[0013] The subject matter disclosed herein includes methods and systems for detecting ballistic impacts with transformers or other types of equipment. Rather than attempt to prevent the assault or detect the presence of assailants, the subject matter disclosed herein seeks to provide reliable detection of and actual attack at the earliest possible opportunity, i.e. immediately after impact of ballistic projectile carrying enough force to breach the main transformer tank or other extremities like conservators or radiators while ignoring routine vibrations and impacts which occur in the normal course of operations.

[0014] FIG. 1 shows an exemplary apparatus for detecting ballistic impacts, according to embodiments of the disclosure. As shown in FIG. 1, a ballistic impact detector 100 includes one or more accelerometer(s) 102 communicatively coupled with one or more processor(s) 104 and one or more transceiver(s) 106. The ballistic impact detector 100 continuously monitors vibrations and impacts resonating throughout equipment to be monitored and discriminates the amplitude of high-energy impacts, such as a bullet strike, from low-energy impacts, such as those that routinely occur during maintenance and regular operations. In the example illustrated in FIG. 1, the ballistic impact detector 100 also includes memory 108, input/output (I/O) circuit(s) 110, and a power supply 112, at least some of which are coupled to one or more data bus(es) 114.

[0015] FIG. 1 also shows an example deployment of the ballistic impact detector 100, i.e., in which the ballistic impact detector 100 is attached to the equipment being monitored 116, which in the example shown in FIG. 1 is a high voltage transformer. Upon detection of a high-energy impact with the equipment being monitored 116 by the ballistic impact detector 100, an alarm message 118 is transmitted to a receiver 120. In some aspects, the receiver 120 may forward the alarm message to a monitoring entity, which may be the operator or another monitoring system.

[0016] In some embodiments, the accelerometer(s) 102 and/or the processor(s) 104 are low-power devices, which may be put into sleep mode in order to save power, such as when the ballistic impact detector 100 is battery powered. In some embodiments, the accelerometer(s) 102 may be programmed to exit sleep mode upon detection of an impact above a specified threshold and notify the processor(s) 104, which may include waking the processor(s) 104 from a sleep mode. In some aspects, the accelerometer(s) 102 may

be able to store the triggering waveform, e.g., the displacement or vibration of the equipment being monitored 116 resulting from the ballistic impact, to local memory within the accelerometer(s) 102 and/or the memory 108. In some aspects, the processor(s) 104 may retrieve the stored waveform information for further analysis and/or for forwarding to the operator or other monitoring entity. For example, in some aspects, prior to sending a notification, the processor(s) 104 may optionally further analyze the impact data from the accelerometer(s) 102, e.g., to confirm that the detected impact is a ballistic impact.

[0017] In some embodiments, the processor(s) 104 then send a notification that a ballistic impact has been detected. In some aspects, the processor(s) 104 may transmit an alarm signal 118 to the on-site receiver 120. In some aspects, upon receipt of the alarm signal 118 the receiver 120 may forward the message to a network-attached server. In some aspects, the network-attached server may propagate the alarm signal to SCADA or other monitoring systems.

[0018] Examples of transmission of an alarm signal 118 by the processor include, but are not limited to, alarm transmission via wired transmission, via wireless transmission (e.g., WiFi, Zigbee, 900MHz), by infrared LED beacon, by cellular transmission, or by some combination thereof. Where the equipment being monitored for ballistic impact is also being monitored by visible or IR cameras, for example, the ballistic impact detector 100 could use an IR LED driven by an I/O port 110 to send a signal that is detected by the cameras. In some aspects, the alarm signal 118 may be a message, e.g., a binary message repeated by the flashing IR LED, that can be decoded by the camera monitoring system. In deployments where the equipment being monitored is not also being monitored by visible or IR cameras, the IR signal can be directed towards a simple, on-site IR detector unit that has wired, wireless, and/or cellular communications capability, with which the IR detector forwards the message to the network operator or other destination.

[0019] In some aspects, the alarm signal 118 may be a wired or wireless message, and may include information such as date of impact, time of impact, geographical location, site ID, information identifying the equipment being monitored (e.g., an equipment ID), information identifying the ballistic monitor itself (e.g., a monitor ID), information characterizing the impact (e.g., confidence level, the number of impacts detected, the

period over which multiple impacts were detected), and the impact data (e.g., the impact waveform from the accelerometer). In some aspects, the alarm signal 118 may include information about the sensor, such as battery status, hardware version number, software and/or firmware version number, or other configuration and/or status information.

[0020] In some aspects, the ballistic impact detector 100 is mounted directly to the equipment being monitored 116. For example, the ballistic impact detector 100 may include a magnetic mount that secures the ballistic impact detector 100 the metal casing of the equipment being monitored 116. In other aspects, the ballistic impact detector 100 may be mounted to the equipment being monitored 116 by fasteners, glue, or other means. In some aspects, the accelerometer(s) 102, processor(s) 104, and transceiver(s) 106 are components of a single unit which is mounted to the equipment being monitored 116. In some aspects, only the accelerometer(s) 102 are mounted to the equipment being monitored 116, and coupled to the processor(s) 104 and transceiver(s) 106 by a wiring harness or other connection such that the processor(s) 104 and transceiver(s) 106 are not directly attached to the equipment being monitored 106.

[0021] In some embodiments, the ballistic impact detector 100 may be battery powered, e.g., the power supply 112 is one or more batteries. In some aspects, the power to the accelerometer, CPU and transmitter is provided by a long-lasting battery, such as a lithium-ion polymer (LiPo) battery. In some aspects, the battery may be charged by solar cells. In some aspects, the battery may be charged by piezo-kinetic generators, e.g., that harvest energy from equipment vibrations. In some aspects, the battery may be charged by induction field harvesting, e.g., by coils harvest energy from the electric fields produced by a transformer. In some aspects, the battery may be charged by connection to an external power source. In some aspects, multiple charging modes may be supported by a single ballistic impact detector 100.

[0022] In some aspects, the ballistic impact detector 100 may be field programmable, e.g., to store information such as geographic location, site ID, equipment ID, ballistic impact detector ID, or other information that may be part of an alarm message. In some aspects, the ballistic impact detector 100 may be remotely programmable via the transmitter. In some aspects, the ballistic impact detector 100 may host a web server that

presents configuration pages as fillable web pages and a security function that prevents unauthorized modification of configuration parameters.

**[0023]** FIG. 2 is a flow chart illustrating an exemplary method 200 for detecting ballistic impacts, according to aspects of the disclosure. As shown in FIG. 2, method 200 may start at block 202 with the ballistic impact detector 100 in an idle and possibly low-power state, where it remains until an impact is detected, at block 204. In some aspects, the impact is detected by the accelerometer(s) 102. In some aspects, the accelerometer(s) 102 are in a low-power or sleep mode, in which case the impact may cause the accelerometer(s) 102 to wake or otherwise leave the low-power mode, in optional block 206.

**[0024]** At block 208, it is determined whether or not the detected impact is a ballistic impact. In some aspects, determining that the impact is a ballistic impact includes determining that the impact was with a force that is above a minimum threshold. In some aspects, a ballistic impact is identified by a displacement or vibration profile having characteristics (e.g., amplitude, frequency, attack or decay shape, ringing frequency, etc.) identified as being associated with ballistic impacts. In some aspects, the accelerometer(s) 102 are configured to wake only when an impact has at least some minimum amount of force, so this step is implied in block 204. In other aspects, the

**[0025]** FIG. 3A is a graph showing an impact waveform for a low-energy impact, e.g., a hammer strike, as recorded by a ballistic impact detector 100, according to aspects of the disclosure, and FIG. 3B is a graph showing an impact waveform for a high-energy impact, e.g., a bullet strike, as recorded by a ballistic impact detector 100, according to aspects of the disclosure. FIGS. 3A and 3B show an example comparison between a non-ballistic impact (FIG. 3A) and a ballistic impact (FIG. 3B). In both FIG. 3A and FIG. 3B, each impact waveform has a maximum amplitude  $A_{MAX}$  and a duration of time in which the metal casing of the equipment vibrates or “rings”  $T_{RING}$ . In the examples shown in FIGS. 3A and 3B, the maximum amplitude of the non-ballistic impact ( $A_{MAX,1}$ ), is less than the maximum amplitude of the ballistic impact ( $A_{MAX,2}$ ), and the ringing time of the non-ballistic impact ( $T_{RING,1}$ ) is shorter than the ringing time of the ballistic impact ( $T_{RING,2}$ ).

**[0026]** Thus, in some aspects, the ballistic impact detector 100 may define a minimum amplitude and minimum ring time which an impact must satisfy before being identified as a possible ballistic impact. It will be understood that other waveform characteristics may be used in addition to or instead of  $A_{MAX}$  and  $T_{RING}$ , such as envelope parameters (e.g., attack decay, sustain, and release), frequency components (e.g., frequency and amplitude of component frequencies as determined by Fourier transform analysis or autocorrelation), and so on. In some aspects, a ballistic impact detector 100 may be programmed for a particular equipment being monitored. For example, the characteristics of the vibrations may differ depending on the size and composition of the equipment to which the sensor is attached; a small transformer may “ring” at a higher frequency and for a shorter time than a large transformer, and so the parameters used to detect a ballistic impact may be adjusted accordingly depending on the size of the transformer. For field programmable ballistic impact detectors, this may be configured at time of installation, for example.

**[0027]** In some aspects, the ballistic impact detector may cooperate with other sensors and/or use other sensor information to determine a confidence value associated with a detected possible ballistic strike. For example, a ballistic impact detector may cooperate with a thermal sensor to determine whether a transformer’s internal temperature is starting to increase after the possible bullet strike; a ballistic impact detector may cooperate with a pressure sensor to detect a drop in coolant pressure within the casing as a result of leak or breach, and so on. In some aspects, the signal sent by the ballistic impact detector may be used to trigger recording of other information about the equipment being monitored, the current environment, or any other information that may be useful, e.g., to help avoid false positives or false negatives in the ballistic impact detection process, to initiate additional detection, deterrence, or mitigation protocols, and so on.

**[0028]** The techniques described herein provide several distinct benefits over the prior art. For example, the ballistic impact detection methods and systems can provide immediate notification of a potentially dangerous and/or destructive future event in time for mitigating actions to be taken. The ballistic impact detectors described herein are small enough and inexpensive enough to be deployed in sufficient numbers to provide a

high level of coverage, e.g., one or more ballistic impact detectors may be economically deployed on each of multiple pieces of equipment. In some configurations, such as battery operated with some means to recharge the battery, a ballistic impact detector is well suited for deployment in remote or hard to reach locations. In some deployments, the ballistic impact detector may be configured to remain in low power mode by default, to extend the life of the battery or reduce the dependence on (or eliminate the need for) an apparatus to recharge the battery.

**[0029]** The example embodiments disclosed herein are illustrative and not limiting. Various implementation details may be changed without departing from the scope of the subject matter contemplated herein.

## EMBODIMENTS

1. A system for detecting ballistic impacts, the system comprising:
  - a ballistic impact detector for attachment to an equipment being monitored, the ballistic impact detector comprising:
    - a memory;
    - an accelerometer communicatively coupled to the memory; and
    - a processor communicatively coupled to the memory and the accelerometer,
      - wherein the accelerometer is configured to detect an impact to the equipment being monitored and notify the processor that the impact was detected, and
      - wherein the processor configured to determine that the impact was a ballistic impact and to transmit an alarm signal to indicate that a ballistic impact was detected.
2. The system of embodiment 1, wherein the accelerometer is configured to enter a low-power mode until an impact is detected, and to exit the low-power mode when the impact is detected.
3. The system of embodiment 2, wherein the accelerometer is configured to exit the low-power mode when the detected impact has an impact force greater than a configured force threshold.
4. The system of embodiment 2, wherein the accelerometer is configured to re-enter the low-power mode after notifying the processor that the impact was detected.
5. The system of embodiment 2, wherein the accelerometer is configured to re-enter the low-power mode after receiving an instruction to re-enter the low-power mode from the processor.
6. The system of embodiment 1, wherein the accelerometer is configured to store data associated with the impact.

7. The system of embodiment 6, wherein the accelerometer is configured to store the data associated with the impact within the accelerometer circuitry.
8. The system of embodiment 6, wherein the data associated with the impact comprises data indicating the maximum force of the impact, the length of time of vibrations of the equipment being monitored after the impact, the impact profile as measured by the accelerometer, or a combination thereof.
9. The system of embodiment 1, wherein the accelerometer is configured to determine whether the impact was a ballistic impact and to notify the processor that the impact was detected only if a probability that the impact was a ballistic impact exceeds a probability threshold.
10. The system of embodiment 9, wherein the processor presumes that the impact was a ballistic impact.
11. The system of embodiment 1, wherein the accelerometer is configured to store the data associated with the impact into the memory.
12. The system of embodiment 11, wherein the processor determines that the impact was a ballistic impact based on an analysis of the impact data in the memory.
13. The system of embodiment 12, wherein the impact data comprises data indicating the maximum force of the impact, the length of time of vibrations of the equipment being monitored after the impact, the impact profile as measured by the accelerometer, or a combination thereof.
14. The system of embodiment 1, wherein the processor transmits the alarm signal via a wired, wireless, or infrared communications link.

15. The system of embodiment 1, wherein the alarm signal contains information associated with the impact.

16. The system of embodiment 15, wherein the information associated with the impact comprises information about the equipment being monitored, information about the ballistic impact detector, information about the current environment, information about the impact, or a combination thereof.

17. The system of embodiment 16, wherein the information about the equipment being monitored comprises at least one of:

- information identifying the equipment being monitored;
- information identifying the location of the equipment being monitored; or
- information about a current or past operational status of the equipment being monitored.

18. The system of embodiment 16, wherein the information about the ballistic impact detector comprises at least one of:

- information identifying the ballistic impact detector;
- information identifying the location of the ballistic impact detector; or
- information about a current or past operational status of the equipment being monitored.

19. The system of embodiment 16, wherein the information about the current environment comprises at least one of:

- a date of impact;
- a time of impact; or
- a weather condition at the time of impact.

20. The system of embodiment 16, wherein the information about the impact comprises at least one of:

- a maximum force of the impact;

- a length of time of vibrations from the impact;
  - a frequency of vibrations from the impact; or
  - a waveform of the impact.
21. The system of embodiment 1, wherein the processor is configured to enter a low-power mode until receiving the notification that an impact was detected, and to exit the low-power mode upon receiving the notification that an impact was detected.
22. The system of embodiment 21, wherein the processor is configured to enter the low-power mode after transmitting the alarm signal to indicate that a ballistic impact was detected.
23. The system of embodiment 1, further comprising a power supply.
24. The system of embodiment 23, wherein the power supply comprises batteries.
25. The system of embodiment 24, wherein the power supply further comprises a battery charging apparatus.
26. The system of embodiment 25, wherein the battery charging apparatus comprises a solar cell, a piezo-kinetic generator, an induction field harvesting apparatus, or a combination thereof.

ABSTRACT

According to one aspect, the subject matter described herein includes \_\_\_\_