Reduction of trip operating time of electronic type ELCB to 9 mili-seconds for safety improvement of electrical facility

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Abstract ELCB (Earth leakage circuit-breaker) is a circuit breaker used in a low-voltage AC (Alternating Current) electrical circuit to provide electric shock protection and to prevent fires from current leakages. Trip operating time of ELCB depends on the magnitude of leakage current and the duration time of leakage accident. In this paper, the circuit and electrical signal after ZCT (Zero-sequence Current Transformer) output terminal of existing ELCBs are analyzed. As a result of measurement, electronic trip type ELCBs in present market have shown up to 27 ms of self-trip operating time under 30 mA of leakage current. This 27 ms of time delay is due to the problem that the IC in electronic circuit detects only the reverse-half cycle of sinusoidal leakage current. In this paper, the authors design a new electronic circuit that minimizes the delay factors of existing circuits. And as a result of an experiment, the trip operating time could be shortened within 9 ms. Shortened trip operating time implies reduction of shock duration of leakage current. Since the electric shock to human body and the outbreak possibility of fire are inversely proportional to square root of shock duration, faster trip operation of ELCB proposed in this paper will contribute to providing shock protection to human body and preventing fires from current leakages. Keywords: ELCB, TOT (Trip Operating Time), electrical shock, shock duration, rated sensitivity current Classification: Power devices and circuits

1. Introduction

With increase of power consumption according to economic growth, importance of electrical safety and the role of ELCB are becoming a major concern. As buildings are becoming larger, not only increased use of electricity but also increased number of the electric branch circuits is threatening the electrical safety [1, 2, 3]. A recent analysis shows that electric shock accidents are more common at low voltage rather than at high voltage and the number of deaths has also been on the rise.

ELCB is a circuit breaker used in a low-voltage AC electrical circuit to provide electric shock protection and prevent fires from current leakages. ELCB is also called “Circuit-breaker incorporating residual current protection” in IEC60947-2 or a “Residual current operated circuit-breakers with integral over current protection for household and similar uses (RCBO)” in IEC61009-1. It is also referred to as a “Ground-fault circuit-interrupter (GFCI)” in UL943 [2, 3].

To protect human body from electric shock, minimizing the leakage trip operating time (TOT from now on) of ELCB is very important [1, 3]. TOT of ELCB is defined by the time elapsed from the instant leakage accident occurs until the time ELCB completely turns off the power source. In IEC 61009-1 standard, the TOT of ELCB is set to less than 30 ms [4, 5, 6, 7, 8].

Leakage TOT below this time level (i.e., 1~29 ms) is not described anywhere in this standard [9, 10, 11, 12, 13]. There are two types of trip mechanism for an ELCB. One is the electronic trip type (electronic type ELCB from now on) and the other is the ZCT trip type (ZCT type ELCB from now on).

Electronic type ELCBs shown in Fig. 1 detect and amplify the leakage current of ZCT output by electronic circuit and transmit a trip signal to ELCB trip coil when the magnitude of the leakage current is larger than threshold value.

ZCT type ELCBs shown in Fig. 2 and Fig. 3 receive the leakage current and amplify it by the turn ratio of its own winding without electronic circuit to directly actuate the trip bar of ELCB.

ZCT type ELCB is more surge-free in general compared to electronic type ELCB because it has no electronic circuit inside. ZCT type ELCB, however, shows longer trip operating time in general when the magnitude of leakage current is relatively small.

Further reduction of trip operating time of electronic type ELCBs is possible using today’s advanced circuit design technology, which significantly can improve the electrical safety.

Longer TOT of ELCB may cause a big property loss by fire or a dangerous electric shock to human body.

The shortest TOT of most electronic type ELCBs in present market exceeds 20 ms. 20 ms corresponds to about

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one and half cycle for 60 Hz AC [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24].

This implies that the shock current flows through human body for at least one cycle or more, which may result in a fatal damage as the case may be. Therefore, shortening the TOT of the ELCB is essential because it directly reduces the duration of current flow through human body. However, existing ELCBs detect only the reverse half cycle of the leakage current inside IC, which makes operation time longer.

It is difficult to shorten the TOT by 15 ms or shorter even though the internal delay factors are optimized. Therefore, it is necessary to re-design the ELCB circuit in order to detect the full-wave of the leakage current.

This paper presents a new electronic circuit structure to reduce the TOT of electronic type ELCB and the performance is tested for a prototype circuit.

2. Full-wave detection of leakage current

2.1 TOT of existing ELCBs

An experiment has been performed for seven existing ELCBs. A leakage current has been supplied for every 0.5 second with 220 V, 60 Hz sinusoidal AC. And the longest TOT out of 30 times of the tests has been recorded. Fig. 4 illustrates the sequence diagram of the ELCB trip operation.

The ELCBs selected for the test are the models specifically designed for human protection from electric shock and the rated sensitivity current are all 30 mA.

Electronic type ELCBs which are triggered by the reference set on IC began to actuate in the range of 21.5 to 24.5 mA [25, 26, 27, 28, 29, 30]. Under 30 mA of rated sensitivity current, the maximum TOTs of existing electronic type ELCB showed 27 ms [3, 25, 26, 27, 28, 29, 30]. The shortest TOT for electronic type ELCB is 15 ms or longer in general despite increase of leakage current.

2.2 Half-wave and full-wave detection

Shortened leakage TOT implies reduction of shock duration of the leakage current, which means reduction of electric shock to the human body and livestock.

Electronic trip type ELCBs in present market have shown up to 27 ms of self-TOT under 30 mA of leakage current. This 27 ms of time delay is due to the problem that the IC in electronic circuit detects only the reverse-half cycle of sinusoidal leakage current.

If the ELCB can detect the full-wave (entire interval (1)∼(4) in Fig. 5-2) of the sinusoidal leakage current, TOT of ELCB considerably can be reduced. In this paper, an electronic circuit by which the full-wave leakage current signal is measurable to reduce TOT of ELCB is developed. In Fig. 5, ELCB trip operation time is shortened through full-wave detection, which is possible by re-design of the electronic circuit of ELCB with two Op-Amps.
2.3 New ELCB with full-wave detectable circuit
The authors designed a new circuit that can detect full-wave of leakage current signal as shown in Fig. 6 and Fig. 7.

New circuit consists of two Op-Amps. #1 Op-Amp receives and amplifies leakage current signal from ZCT output. #2 Op-Amp receives the same leakage current signal that #1 Op-Amp receives but reverses its phase angle by 180° and again amplifies it. Both #1 and #2 amplifiers adopt a filter circuit that eliminates high-frequency noise as shown in Fig. 6. IC latch circuit compares the amplified leakage signal with preset threshold value to actuate the trip circuit of ELCB.

Existing electronic type ELCBs detect only one half cycle (about 8.3 ms) of the leakage signal from ZCT output. Therefore, the TOT may exceed 30 ms-standard in case signal detection fails within first reversed-half cycle.

However, the IC latch output proposed in Fig. 6 always can be operated within 8.3 ms because two bi-directional IC inputs always enable successful detection of the first half cycle of sinusoidal wave.

Full-wave detection function of new ELCB trip circuit proposed in this paper has shown a stable trip operation without failure within the range of 9 ms.

Prototype ELCB circuit made by the authors is shown in Fig. 7.

The electronic switch used for prototype ELCB is SCR BT169G (Manufacturer: Philips).

Gate controlled turn-on time of BT169G is approximately 2 micro-second and commutated turn-off time is approximately 100 micro-second [31] that can be ignored compared to ToT of ELCBs.

3. Analysis
The authors made two prototype ELCB circuits (New-ELCB1 and New-ELCB2 in Table I) with two bi-directional IC inputs. A test has been performed to measure the TOT and the results have been compared with two existing ELCDs in the current market. (Existing-ELCB1 and Existing-ELCB2 in Table I)

We can see in Table I that 19.8 ms of existing TOT of existing ELCBs can be reduced to 6.0 ms with new ELCBs with two OP-amps. Trip operation time of two existing ELCBs was measured from a minimum of 12 ms to a maximum of 27 ms. (Range of measurement = 15 ms)

Trip operation time of two new ELCBs was measured from a minimum of 4 ms to a maximum of 9 ms. (Range of measurement = 5 ms) Existing ELCB1 was measured at 19.8 ms at 22.7 mA and existing ELCB2 was measured at 18.3 ms at 21.6 mA. Fig. 8 illustrates the graph of test number vs TOT of ELCBs.

We also made test to see if the new circuit would reduce the TOT to 0.6 ms. Table I shows that the new circuit can reduce the TOT to 6.0 ms and it is significantly lower than the existing ELCB.

![Fig. 6. ELCB circuit with two Op-Amps.](image)

![Fig. 7. PCB layout of new ELCB circuit](image)

![Table I. Test results of ELCB TOT](table)

| Test number and TOT [ms] | Test number and TOT [ms] |
|--------------------------|--------------------------|
| ELCB Current | ELCB Current |
| 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 | 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 |
| New-ELCB1 mA | New-ELCB2 mA |
| 22.5 | 21.3 |
| 8 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| X | R |
| 6.9 | 5 |
| 6.0 | 5 |
| Existing-ELCB1 mA | Existing-ELCB2 mA |
| 22.7 | 21.6 |
| 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| 19.8 | 15 |
| 18.3 | 15 |

![Fig. 8. Test number vs TOT](image)

As we see in Table I, the mean value of TOT for new ELCB1 was measured at 6.9 ms at 22.5 mA and new ELCB2 was measured at 6.0 ms at 21.3 mA.

These imply that the TOT of existing ELCBs can be reduced almost to 1/3 (≒ three times faster) with newly-designed ELCBs.
Through the proposed electronic-type ELCB with full-wave detection can drastically reduce ToT, however, we can imagine the following disadvantages.

Firstly, additional OP-amp for full-wave detection may increase production cost of ELCB electronic circuit.

Secondly, additional OP-amp circuit for full-wave detection may results in narrower layout space in PCB.

Thirdly, electronic circuit of ELCB may become vulnerable to attack of external surge or noise due to cramped layout space.

The authors tested a prototype ELCB including ‘Surge Immunity Test’ and ‘Test of Immunity to conducted disturbances induced by radio-frequency fields’ and ‘Test of Radiated, radio-frequency electromagnetic field’ at an authorized testing institute [32], which showed no malfunction or other unusual behavior of prototype ELCB. Detailed test items of prototype ELCB is listed in Appendix.

4. Conclusion

TOT of ELCB depends on the magnitude of leakage current and the duration time of leakage accident.

The ICs in electronic type ELCB of present market are operated only within the reverse half cycle of sinusoidal leakage current. For fundamental reduction of TOT of ELCB, however, it is essential for the ICs to be able to detect the full-wave input signal.

The authors in this paper developed an electronic circuit in which the delay factors are optimized and by which the full-wave leakage signal is measurable to obtain minimum TOT.

As the result of experiment, the longest TOT of existing ELCBs was 27 ms under 30 mA of rated sensitivity while the longest TOT of newly developed ELCB showed 9 ms, which implies TOT of ELCB can be improved three times faster. Needless to say, the faster the TOT of ELCB, the less the electrical damage to human body.

Faster trip operation of ELCB proposed in this paper will contribute to preventing property loss by fire and electric shock to human body from current leakages accidents.

In particular, it would significantly improve the electric safety in wet areas such as a swimming pool, medical institutions and welfare facilities for children and the aged.

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Conflicts of interest

The authors declare no conflict of interest.

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Appendix

1. Electromagnetic compatibility (EMC) - Requirements for household appliances, electric tools and similar apparatus - Part 1: Emission
2. Electromagnetic compatibility (EMC) - Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test
3. Electromagnetic compatibility (EMC) - Part 4-3: Testing and measurement techniques - Radiated, radio-frequency, electromagnetic field
4. Electromagnetic compatibility (EMC) - Part 4-4: Testing and measurement techniques - Electrical fast transient, burst immunity test
5. Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test
6. Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields