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# Use of the Traditional Wattmetric Function in Networks with Zig-Zag Transformer Grounding

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**Abstract.** The earliest electrical protection systems consisted of simple overcurrent relays (functions 50/51) that measured only the magnitude of the current.
Later, European engineers—particularly in Germany and the Nordic countries, where compensated-neutral networks were common—began to adapt the directional principle to zero-sequence currents (function 67N). The purpose was to determine whether the ground fault was located within the protected section, thus avoiding unnecessary tripping in other parts of the system [1–4].
In systems with isolated or Petersen-coil grounded neutrals, the 67N function provides excellent selectivity but when a system is grounded through a zig-zag transformer, selectivity becomes even more challenging if the protected line has significant capacitive contribution [5].
This paper presents the existing difficulties in achieving selectivity in networks grounded through zig-zag transformers combined with lines that carry high capacitive current. Once the problem is described, a simple and cost-effective solution is proposed based on the wattmetric protection function to obtain an appropriate selectivity. The solution presented in this paper is already implemented in the field.

**Key words.** Zig-Zag transformer, Wattmetric protection, Forward fault, Reverse fault, Zero-sequence.

| | |
|---|---|
| 0 | Zero-sequence component of the three-phase system. |
| $\boldsymbol{V}$ | Voltage phasor. |
| $\boldsymbol{I}$ | Current phasor. |
| $R_F$ | Fault resistance. |
| R | Resistance |
| L | Inductance. |
| C | Capacitance |

## 1. Introduction

The earliest electrical protection systems consisted of simple overcurrent relays (ANSI functions 50/51), which could measure only the magnitude of the current. These devices operated on straightforward electromechanical principles, providing protection exclusively against excessive currents caused by short circuits or overloads. At that time, the electrical distribution networks were predominantly radial and solidly grounded, which made the direction of current flow during fault conditions obvious—it invariably flowed from the source toward the faulted point. As a result, directional control was not considered necessary for protection coordination.

With the progressive development of more complex power networks, the use of systems with isolated neutrals and the introduction of Petersen coils became increasingly common. In such configurations, the resulting ground-fault currents were relatively small, and their flow paths depended strongly on the system's impedance and capacitive coupling, leading to situations in which currents could circulate in several directions simultaneously. Consequently, the selectivity and discrimination of conventional overcurrent protection systems became far more difficult to achieve.

This challenge motivated the evolution of directional protection schemes. European engineers enhanced the classical overcurrent principle by incorporating directional elements sensitive to zero-sequence components. This advancement gave rise to the ANSI function 67N, known as directional ground-fault protection. By evaluating the phase relationship between zero-sequence voltage and current, these relays were able to determine whether a fault originated within the protected line section or outside of it, thus preventing unnecessary tripping elsewhere in the network [1–4].

In systems with isolated or Petersen-coil grounded neutrals, the 67N function provides highly reliable and selective operation, ensuring precise discrimination of ground-fault locations even when currents are of low magnitude. However, when the network is grounded through a zig-zag transformer, achieving correct selectivity becomes considerably more challenging—particularly when the protected line exhibits a high degree of capacitive current contribution. [5].

This paper addresses these difficulties in obtaining accurate selectivity for networks employing zig-zag transformer grounding in conjunction with lines with high capacitive current. After describing and analysing the problem from both theoretical and practical perspectives, a straightforward and cost-effective solution approach is proposed, capable of improving protection coordination without the need for sophisticated or expensive equipment. The solution presented in this paper is already implemented in the field.

## 2. Description of the problem with the selectivity

This section details the problem associated with selectivity for networks employing zig-zag transformer grounding in conjunction with lines with high capacitive current [5].

### *A. Primary scheme*

Fig. 1 illustrates the primary scheme of a zig-zag grounded system where:

Zz, represents the zig-zag transformer;
Yn/d transformer, represents the power transformer type;
CT, represents the current transformer;
VT, represents the voltage transformer;
$C_1$, represents the capacitance of the protected line;
$C_2$, represents the capacitance of the local source impedance;
$F_1$, represents a forward fault in the protected line;
$F_2$, represents a reverse fault;

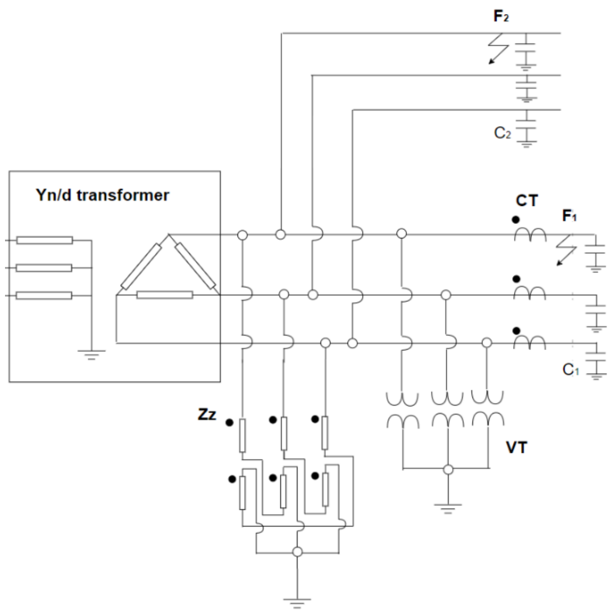


Fig. 1. *Simplified network scheme.*

### *B. Analysis of the angle between the zero-sequence voltage and current in F1 forward fault*

When a single-phase-to-ground fault occurs on phase A, the corresponding sequence networks for phase A are connected in series but in this type of scheme, we are only concerned with the zero-sequence network; therefore, Fig. 2 exclusively represents the zero-sequence network:

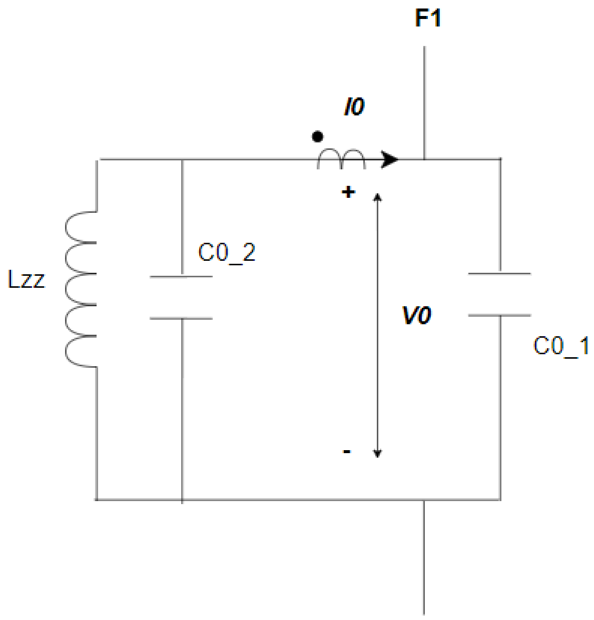


Fig. 2. Zero-*sequence network in forward fault.*

Where:

$\boldsymbol{V_0}$, represents the zero-sequence measured voltage;
$\boldsymbol{I_0}$, represents the zero-sequence measured current;
$L_{ZZ}$, represents the inductance of the zig-zag transformer;
$C_{0\_1}$, represents the zero-sequence capacitance of the protected line;
$C_{0\_2}$, represents the zero-sequence capacitance of the local source impedance;

In this scenario, the equation (1) represents the angle between the zero-sequence current and the zero-sequence voltage:

$$angle\left(\frac{I_0}{V_0}\right) = angle\left(\frac{\mathrm{j}}{\omega \cdot \mathrm{L_{zz}}} - \omega \cdot \mathrm{C_{0\_2}} \cdot \mathrm{j}\right) \tag{1}$$

Where:
$\mathrm{j} = \sqrt{-1}$
$\omega$, represents the angular frequency of the system

In the event that the equation (2) is fulfilled,

$$\frac{1}{\omega^2 \cdot \mathrm{C_{0\_2}}} > \mathrm{L_{zz}} \tag{2}$$

the angle between the homopolar current and voltage will be equal to 90°. Fig. 3 represents the angle between zero-sequence voltage and zero-sequence current in a forward fault condition when equation (2) is fulfilled:

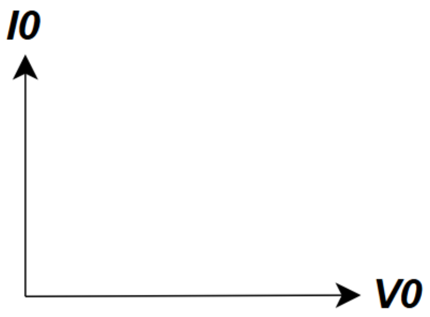


Fig. 3. *Fasor diagram when equation (2) fulfilled.*

On the other hand, if the equation (3) is fulfilled:

$$\frac{1}{\omega^2 \cdot C_{0\_2}} < L_{zz} \tag{3}$$

In this case the angle is -90º. Fig. 4 represents the angle between zero-sequence voltage and zero-sequence current in a forward fault condition when equation (3) is fulfilled:

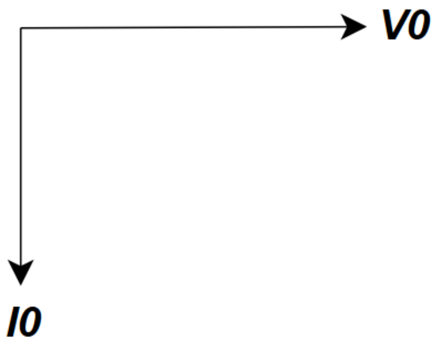


Fig. 4. *Phasor diagram when equation (3) fulfilled.*

*C. Analysis of the angle between the zero-sequence current and voltage in F2 reverse fault*

The resulting zero-sequence network representation for a phase-A ground fault at location F2 is shown in the Fig. 5:

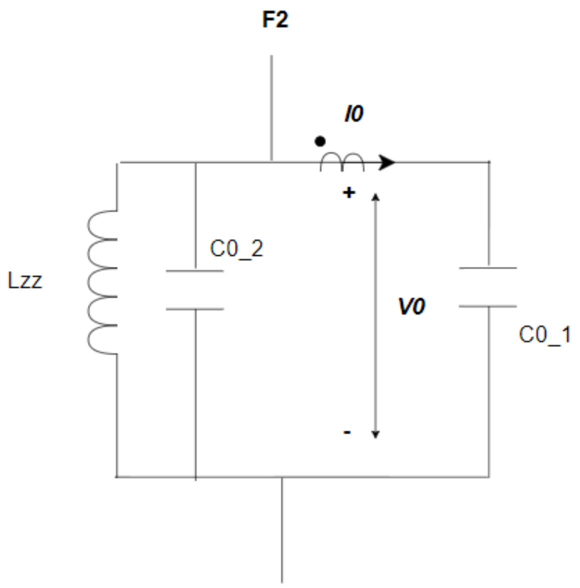


Fig. 5. *Zero-sequence network in reverse fault.*

In this scenario, the angle between the zero-sequence current and the zero-sequence voltage will be represented by the equation (4):

$$arg\left(\frac{I_0}{V_0}\right) = arg\left(\omega \cdot C_{0\_1} \cdot j\right) \tag{4}$$

The angle between the zero-sequence current and voltage will be equal to 90º. Fig. 6 represents the angle between zero-sequence voltage and zero-sequence current in a reverse fault condition:

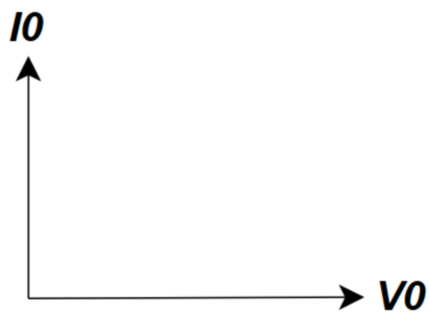


Fig. 6. *Phasor diagram in reverse fault.*

*D. Comparison between the forward and reverse fault*

In the case of a reverse fault, the angle between the zero-sequence current and voltage is observed to be equal to 90°, due to the capacitive nature of the line in zero-sequence network. Conversely, in the case of a forward fault, depending on the inductance of the zig-zag transformer $L_{zz}$ and the equivalent zero-sequence capacitance of the local source impedance $C_{0\_2}$, it may occur that the angle could be equal to 90° or -90°. If the angle is equal to 90°, the directional relay is unable to discriminate between a forward fault and a reverse fault.

## 3. Proposed solution

In the previous section, it has been demonstrated that, depending on the inductance of the zig-zag transformer and the zero-sequence capacitance of the local source, it is possible that, in the presence of a grounding system with a zig-zag transformer and high capacitive current in the lines, the 67N function may not be able to discriminate between a forward fault and a reverse fault. In this situation, the first step of the proposed solution is to provide a grounding resistor connected between the neutral point of the zig-zag transformer and ground. Fig. 7 represents a zig-zag transformer with a resistance installed between the neutral of the zig-zag transformer and ground:

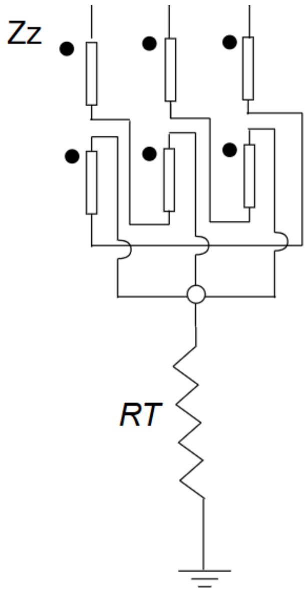


Fig. 7. Zig-zag transformer with resistance in series

Where:

$R_T$, represents the grounding resistor.

By introducing this new resistive characteristic to the fault, the use of 67N wattmetric directional protection becomes suitable for resolving the issue of selectivity.

To simplify the equations, the series ground impedance will be converted into an equivalent parallel impedance represented in the Fig. 8:

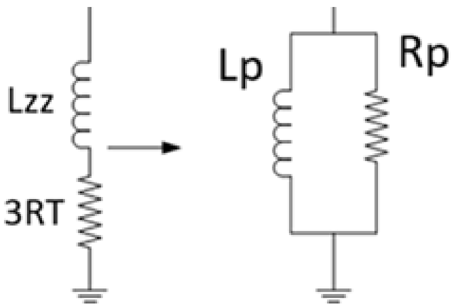


Fig. 8. *Change from series to equivalent parallel impedance*

When the grounding resistor is installed, the sequence network is arranged as represented in Fig. 9 in the event of a forward fault:

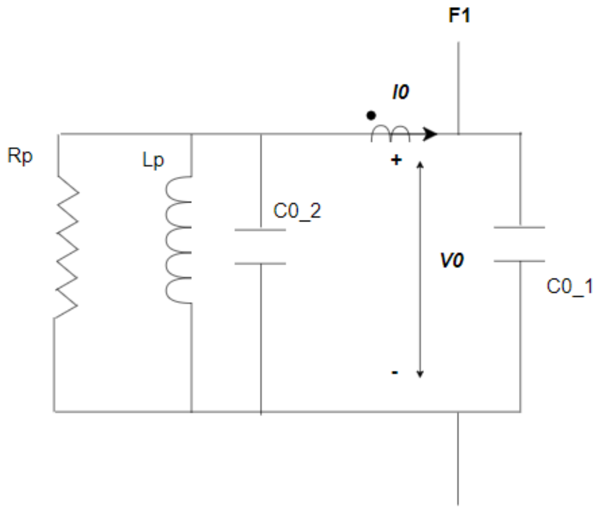


Fig. 9. Zero-*sequence network in forward fault with resistance in the grounding.*

The values of $R_P$ and $L_P$ are represented by the equation (5) and (6):

$$R_P = \frac{(3R_T)^2 + \omega^2 L_{ZZ}^2}{3R_T} \tag{5}$$

$$L_P = \frac{(3R_T)^2 + \omega^2 L_{ZZ}^2}{\omega^2 L_{ZZ}} \tag{6}$$

Once a resistive characteristic is provided to the network, we can calculate the zero-sequence power that would be obtained in the event of a forward fault. The calculated zero-sequence power would be represented in equation (7):

$$P_0 = Re(\boldsymbol{V_0} \cdot \boldsymbol{\bar{I}_0}) = -\frac{|\boldsymbol{V_0}|^2}{R_P} \tag{7}$$

Where:

$P_0$, represents the calculated zero-sequence power;
$\boldsymbol{V_0}$, represents the zero-sequence measured voltage;
$\boldsymbol{\bar{I}_0}$, represents the conjugate of the measured zero-sequence current;

In the event of a reverse fault, there will be almost no measurement of zero-sequence power due to the low resistive and conductive nature of the cables.

To distinguish between forward and reverse faults, it is essential to define an adequate zero-sequence power threshold. As a reference, it can be assumed that in the event of a ground fault with zero fault resistance, the zero-sequence voltage in that case corresponds to the rated voltage of the system. So, in this case the mesured zero-sequence power will be represented by the equation (8):

$$P_{0\_R} = -\frac{V_N^2}{R_{new}} \tag{8}$$

An appropriate threshold could be 7.5% of the calculated $P_{0\_R}$, assuming that the zero-sequence voltage is equal to the system's nominal phase-to-ground voltage.

$$P_{0\_setting} = 0.075 \cdot P_{0\_R} \qquad (9)$$

Where:
$P_{0\_R}$, represents the zero-sequence reference power.
$V_N$, represents the phase to ground nominal voltage.
$P_{0\_setting}$, represents the zero-sequence power setting.

If the calculated power is lower than the set value, a forward trip will be initiated.

## 4. Study cases

This section demonstrates the validity of the proposed algorithm. This way, it includes the performed simulations, in a real-world substation.
Fig. 10 shows the MATLAB model used in the study cases.

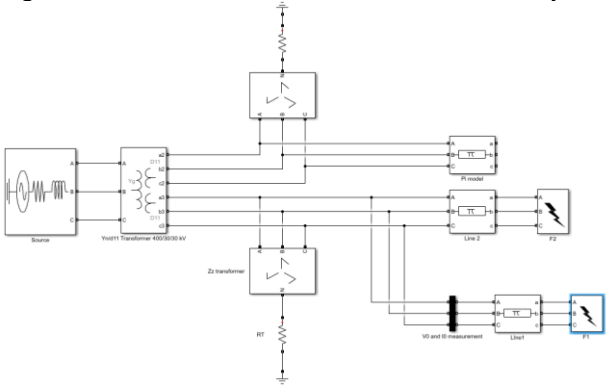

Fig. 10. MATLAB model

This Matlab model simulates a real substation in Portugal where the source voltage is equal to 400 kV. The power transformer is rated at 400/30/30 kV with a Yn/d11/d11 connection configuration. The grounding transformer has a zero-sequence inductance equal to:

$$L_{zz} = 0.14\ Henry$$

The equivalent local source's zero-sequence capacitance equals in an event of a forward fault equals to:

$$C_{0\_2} = 3.75 \cdot 10^{-6}\ Faraday$$

The protected line has a total capacitance equal to:

$$C_{0\_1} = 8.8974 \cdot 10^{-6}\ Faraday$$

In the first simulation, the grounding resistance is zero:

$$R_T = 0\ \Omega$$

In this situation, the following value will be calculated:

$$\frac{1}{\omega^2 \cdot C_{0\_2}} = 2.7018 \qquad (9)$$

Since $L_{zz}$ is lower than the value calculated in (9), the angle between the zero-sequence current and the zero-sequence voltage is the same in both the forward and reverse fault cases, making it impossible to correctly determine the fault direction. In this first simulation, a forward A phase to ground fault occurs at 1 s and lasts for 0.5 s. Afterwards, a reverse A phase to ground fault takes place at 2 s and lasts for 0.5 s. In both cases, the fault resistance is null. The angle between the zero-sequence current and the zero-sequence voltage in both scenarios is 90º so it is impossible to see a difference between a forward and reverse fault. Fig. 11 represents the angle between the zero-sequence current and zero-sequence voltage:

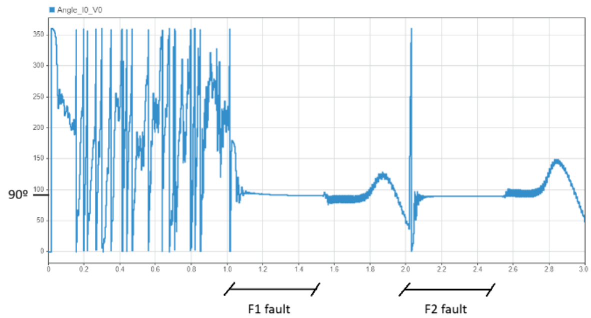


Fig. 11. Angle between the zero-sequence current and zero-sequence voltage in the case of $R_T = 0\ \Omega$.

In the second simulation, the grounding resistance is equal to 35 **Ω**:

$$R_T = 35\ \Omega$$

In this situation, the angle between the zero-sequence current and the voltage in the case of a forward A phase to ground fault is approximately 165º, while in the case of a reverse A phase to ground fault it remains at 90º. Fig. 12 represents the angle between the zero-sequence current and zero-sequence voltage:

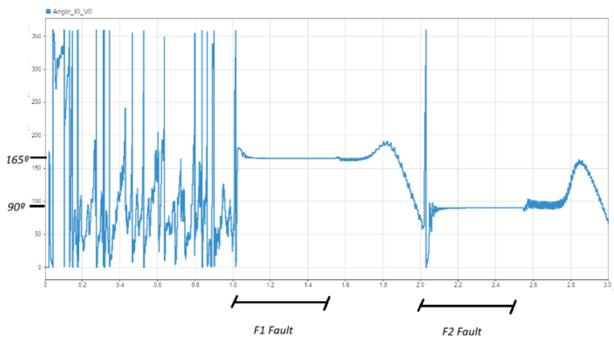


Fig. 12. Angle between the zero-sequence current and the zero-sequence voltage in the case of RT = 35 **Ω**

If we calculate the theoretical zero-sequence power that should be obtained in the case of a forward fault, it would be equal to:

$$P_{0\_R} = -\frac{{V_N}^2}{R_{new}} = -2.43MW$$

Where:

$$V_N = \frac{30}{\sqrt{3}} \mathrm{kV}$$

$$R_P = \frac{(3R_T)^2 + \omega^2 L_{ZZ}{}^2}{3R_T} = 123.423\Omega$$

If it is compared with the simulation, it can be observed that these two values are very similar in the case of a forward fault. Fig. 13 represents the calculated value of zero-sequence power:

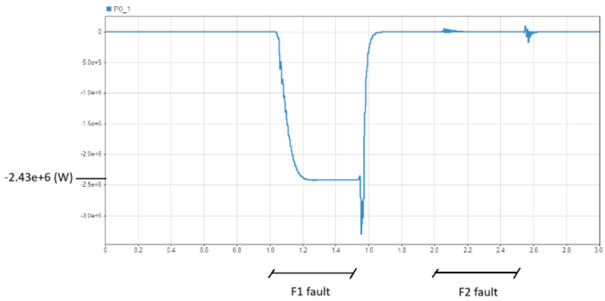


Fig. 13. Zero-sequence power in the case of a forward fault and a reverse fault

In the case of a reverse fault, the measured power is practically negligible.
The proposed threshold for this case is equal to:

$$P_{0\_setting} = 0.075 \cdot P_{0\_R} = -0.1823\ MW$$

If the measured power is lower than this value, the wattmetric function would indicate a forward trip.
In the following table, the test has been carried out for different values of fault resistance in a forward A phase to ground faults and in a reverse A phase to ground faults. The first column represents the fault location. The second column represents the fault resistance. The third column represents the measured zero-sequence power. The fourth column represents the output forward trip of the wattmetric function.

Table I. – Fault cases.

| FAULT TYPE | Rf(Ω) | P0 (MW) | Forward Trip |
|---|---|---|---|
| Forward | 0 | -2.43 | Yes |
| | 25 | -0.975 | Yes |
| | 50 | -0.52 | Yes |
| | 75 | -0.325 | Yes |
| | 100 | -0.225 | Yes |
| Reverse | 0 | 0 | No |
| | 25 | 0 | No |
| | 50 | 0 | No |
| | 75 | 0 | No |
| | 100 | 0 | No |

With the simulations performed, it can be observed that the higher the fault resistance, the lower the measured power. Nevertheless, the function exhibits good performance even with a fault resistance of up to 100 Ω.

## 5. Conclusions

This paper presents a simple and cost-effective solution for cases where grounding is implemented through a zig-zag transformer in networks with high capacitive current in the lines.
By installing an appropriate grounding resistor and employing the traditional wattmetric function, it has been possible to efficiently and effectively discriminate between forward and reverse faults even in faults with high fault resistance.
In this paper, its effectiveness has been demonstrated through theoretical calculations and Matlab simulations of a real network example.
The solution presented in this paper is already implemented in the field.

## Acknowledgement

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