146 *KIEE International Transactions on PE, Vol. 4-A No. 3, pp. 146~151, 2004*

Numerical Algorithm for Power Transformer Protection

Chul-Won Park †, Hee-Seok Suh* and Myong-Chul Shin**

Abstract - The most widely used primary protection for the internal fault detection of the power transformer is current ratio differential relaying (CRDR) with harmonic restraint. However, the second harmonic component could be decreased by magnetizing inrush when there have been changes to the material of the iron core or its design methodology. The higher the capacitance of the high voltage status and underground distribution, the more the differential current includes the second harmonic during the occurrence of an internal fault. Therefore, the conventional second harmonic restraint CRDR must be modified. This paper proposes a numerical algorithm for enhanced power transformer protection. This algorithm enables a clear distinction regarding internal faults as well as magnetizing inrush and steady state. It does this by analyzing the RMS fluctuation of terminal voltage, instantaneous value of the differential current, RMS changes, harmonic component analysis of differential current, and analysis of flux-differential slope characteristics. Based on the results of testing with WatATP99 simulation data, the proposed algorithm demonstrated more rapid and reliable performance.

Keywords: flux-differential current slope, internal fault, magnetizing inrush, numerical algorithm, power transformer protection

1. Introduction

The power transformer is a significant piece of apparatus in a power system. It reveals a lower accident ratio than other system equipment, but once an accident occurs, it causes long-term operation failure and economic loss [1]. Therefore, protective relaying, which detects internal faults in a power transformer, is highly important. The commonly encountered transformer protection arrangement is based on the differential current principle. The most widely used primary protection for the internal fault detection of the power transformer is current ratio differential relaying (CRDR) with harmonic restraint. Second harmonic restraint CRDR is based on the fact that the 2nd harmonic is usually predominant under all energization conditions [2]. However, the 2nd harmonic component could be decreased by magnetizing inrush when there have been changes to the material of the iron core or its design methodology. The higher the capacitance of the high voltage status and underground distribution, the more the differential current includes the 2nd harmonic component during the occurrence of an internal fault. Therefore, the conventional harmonic restraint method requires modification [3, 4].

Alternatively, relay engineers are interested in intelligent electronic devices (IED), which are the core of a substation automation system (SAS). IEDs for data acquisition, protection, metering, and control have gained widespread acceptance and are recognized as being essential to the efficient and cost-effective operation and management of the substation [5-7].

Recently, in order to overcome such problems, several new approaches utilizing AI technique have been developed [8]. The DWT-based algorithm has been reported [3]. Seung-Jae Lee et al. also proposed a voltage-current trend-based protective relaying algorithm [4]. Most of these approaches are liable to false operation during magnetizing inrush with low 2nd harmonic component and internal faults with high 2nd harmonic component.

This paper proposes a numerical relaying algorithm by trend of voltage and differential current, harmonics, and flux-differential current slope characteristics [4, 8, 9]. This improved algorithm was closely examined and compared with various other algorithms, such as the fuzzy logic based algorithm, the discrete wavelet transform based algorithm, and the conventional current percentage differential relaying algorithm [3, 8, 10] in the various categories of fault detection timing, feature extraction and so on.

2. Numerical Protection Algorithm for Power Transformers

2.1 Flux-Differential Current Slope Characteristic

Flux-current characteristic essentially utilizes the flux-current relation of the transformer to obtain the restraint

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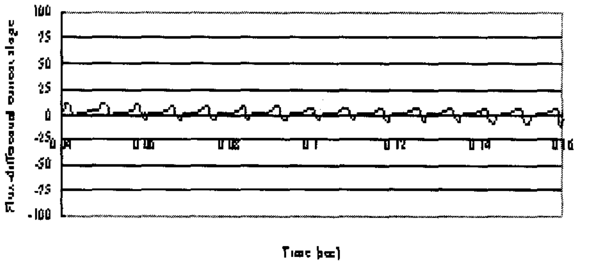
Received April 7, 2004; Accepted August 26, 2004

function for blocking malfunction of the relay under the transformer transient state [9]. However, residual flux in the core of the transformer is not zero. In essence, the flux-differential current itself can be determined by its slope in the flux-differential current plain [8]. That is to say, the flux-differential current slope $d\phi_k/di_k$ at the kth sample is defined by

$$\left(\frac{d\phi}{di_d}\right)_k \cong \frac{\phi_k-\phi_{k-1}}{i_{p.k}-i_{p.k-1}} = \frac{\left\{\frac{\Delta t}{2}\left(v_{p.k}+v_{p.k-1}\right)-L_p\left(i_{p.k}-i_{p.k-1}\right)\right\}}{\left(i_{p.k}-i_{s.k}\right)-\left(i_{p.k-1}-i_{s.k-1}\right)} \qquad (1)$$

where subscripts p and s represent primary side and secondary side of the power transformer, Δt is sampling interval, i_d is differential current, ϕ is flux, and L_p is the leakage inductance of the primary winding at kth sample.

Fig. 1 is plotted by calculating the flux-differential current slope with relaying signals obtained from WatATP 99 simulation by the selected transformer in this paper. X and Y axes indicate time and flux-differential current slope, respectively. We can see that calculated values arrive close to zero in the case of steady state; values fluctuate between approximately -15 to 0 during energization of the transformer, while they remain around -15 under internal fault. From the transition characteristics of the calculated flux-differential current slope, distinctness may be kept concerning fault conditions as well as magnetizing inrush and steady state.



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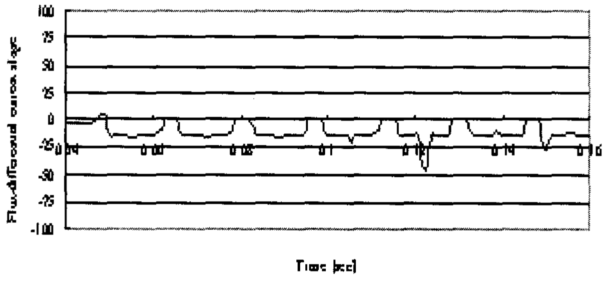

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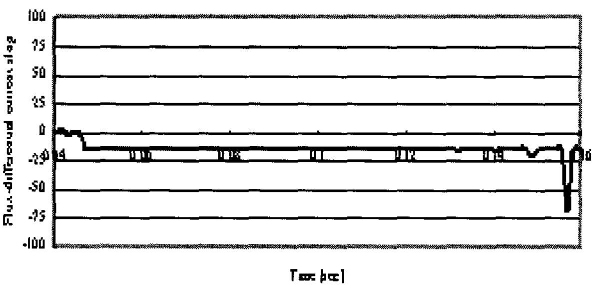


(c)

Fig. 1 Transition characteristics of flux-differential current slope (a) Steady state (b) Energized condition (c) Internal fault

2.2 Numerical Relaying Algorithm

Fig. 2 illustrates the flow chart of proposed relaying algorithm by analyzing RMS fluctuation of terminal voltage, instantaneous value of the differential current, RMS changes, harmonic component of differential current, and the flux-differential characteristic slope. It consists of initialization, data input, computational data, fault discrimination between disturbance and internal faults, and trip signal issue. I-CNT and F-CNT indicate inrush counter and fault counter, respectively. The several computed values in this study are used to clear fault detection by comparison with the predefined threshold value.

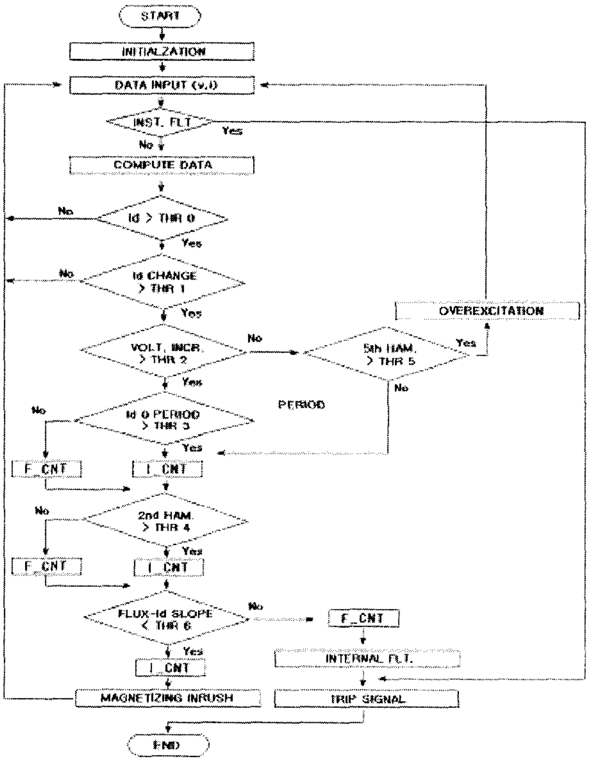


Fig. 2 Flow chart of an adaptive relaying algorithm for clear fault discrimination

3. Simulation Study

3.1 Power System Model

Fig. 3 presents the selected power system model in this paper. For an evaluation of the proposed relaying algorithm, we used the transformer inrush currents, internal fault currents, and voltage signals. The sampling rate of 16 samples and 144 samples per cycle were used in the WatATP99 simulation package. The 3-phase, 45/60MVA, 154/23KV transformer is simulated by the saturable transformer model and the BCTRAN routine [11, 12].

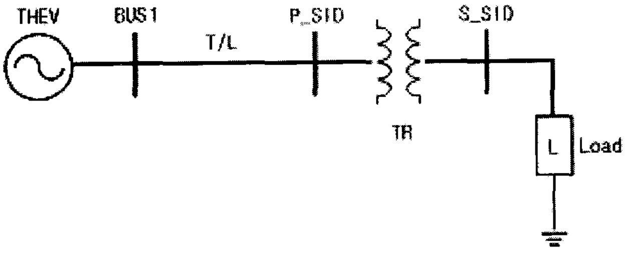
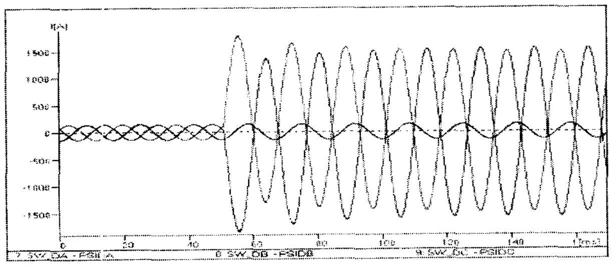


Fig. 3 Simulation model system

3.2 Evaluation Performance

Fig. 4(a) shows the three phase primary currents when turn-to-ground fault occurs at the location of the fault defined between 20% and 80% on the HV winding of phase B [12]. It is obvious that the voltage of faulted phase would decrease while the current of faulted phase would increase following fault inception. Fig. 4(b) demonstrates the results of fault discriminant using the proposed algorithm, defuzzified value by the fuzzy logic-based algorithm [8], and value of detail 1 ratio by the DWT-based algorithm [3]. According to the flux-differential current slope characteristic at the last step of the proposed algorithm, internal fault is detected when the values are below threshold value –7.5, which are repeated more than six times. As shown in Fig. 4(b), fault detection time of the proposed algorithm takes place at about 8.34ms (at the 6th sample point). The trip operation time is approximately half a cycle. We can see that fault detection by the proposed algorithm is quite rapid.



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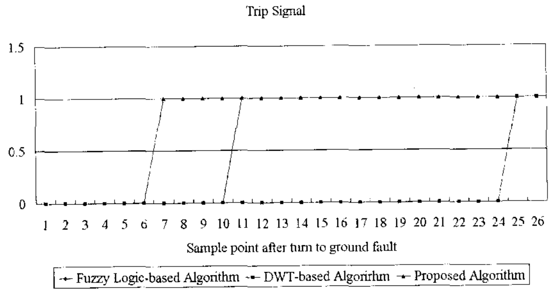
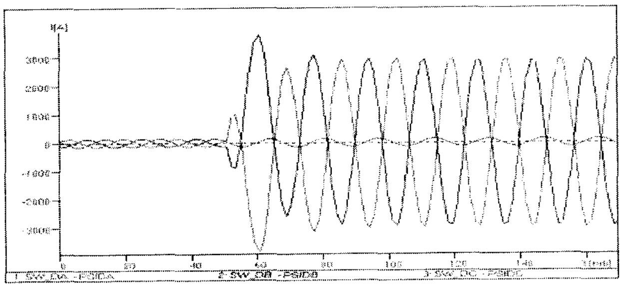


(b)

Fig. 4 Turn-to-ground fault (a) Three phase primary currents during turn-to-ground (b) Trip signals

Fig. 5(a) shows the three phase primary currents when turn-to-turn fault occurs at the fault in winding located within the 5:80:15 part on the HV winding of phase B. Fig. 5(b) demonstrates the results of fault detection time using the proposed algorithm, the fuzzy-based algorithm, and the DWT-based algorithm for turn-to-turn fault. As shown in Fig. 5(b), the relay issues the trip signal at about 8.34ms. The result of fault detection time is similar to the result of turn-to-ground fault mentioned previously.



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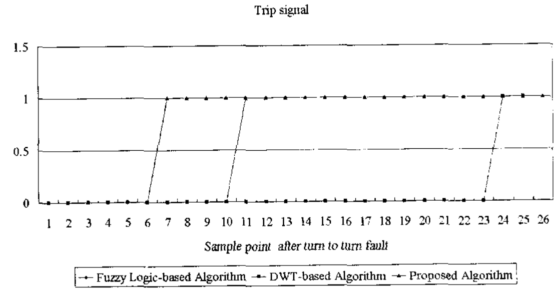
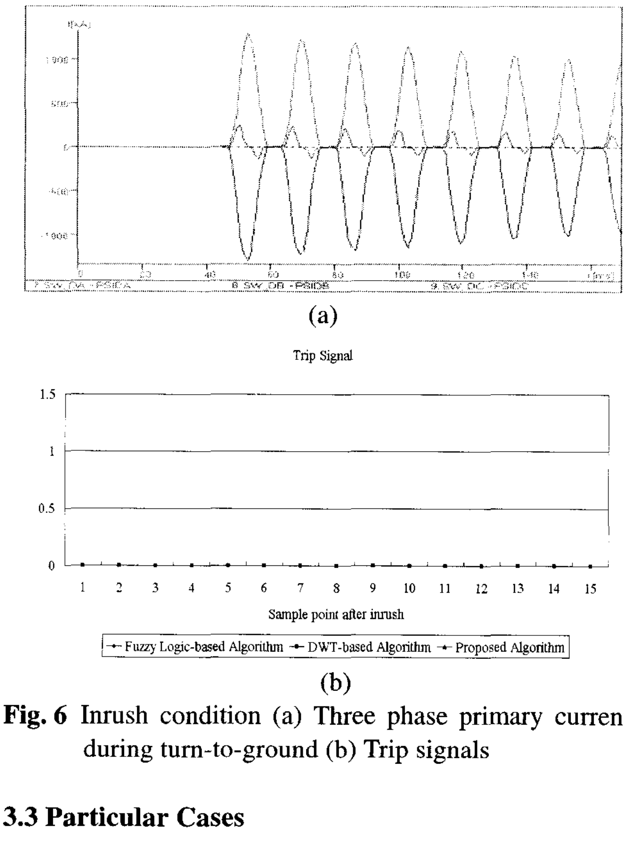


(b)

Fig. 5 Turn-to-turn fault (a) Three phase primary currents during turn-to-turn fault (b) Trip signals

Fig. 6(a) shows the three phase primary currents when energizing at about 0.0444sec. The magnitude of inrush current is very large at voltage inception angle of 0 degrees and the inrush current is to be found at the energized side. It contains a substantial amount of harmonics, particularly the second harmonic. Fig. 6(b) displays the results of trip signals using both the proposed algorithm and the comparative algorithm. As seen in Fig. 6(b), the trip command signal is not issued in all of the algorithms. Then the inrush discriminant by the proposed algorithm is very speedy at two-thirds a cycle following energization.



(a)

(b)

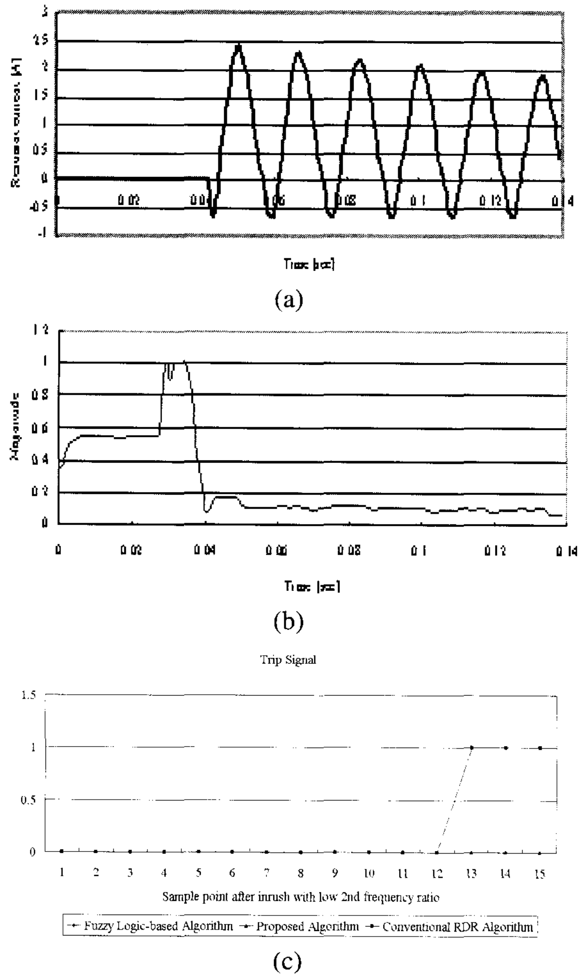
Fig. 6 Inrush condition (a) Three phase primary currents during turn-to-ground (b) Trip signals

3.3 Particular Cases

This section describes the extraordinary points proposed in particular cases. The specific waveforms are generated by the means of addition or removal prescribed 2nd harmonic component by the MS Excel program from WatATP99 simulation data.

Fig. 7(a) shows A phase current signal in the primary side during inrush with low 2nd frequency ratio. Fig. 7(b) indicates ratio of second frequency over fundamental frequency during inrush. X and Y axes indicate time and magnitude of Fl/F2, respectively. During the modified inrush condition, the ratio of 2nd frequency component over 1st frequency component using DFT filter extraction is nearly 10%. Fig. 7(c) presents the results of fault discrimination using the proposed algorithm and the comparative algorithm, when energizing with low 2nd frequency ratio. As seen in Fig. 7(c), the proposed algorithm operates well while the conventional RDR mal-operates.

Fig. 8(a) shows A phase current signal in the primary side during terminal to ground fault with high 2nd frequency ratio at about 0.0472sec. Fig. 8(b) represents nearly 35% on the ratio of 2nd frequency component over 1st frequency component. Fig. 8(c) illustrates the results of fault discrimination by the proposed algorithm, the fuzzy algorithm, and the conventional RDR. As shown in Fig. 8(c), the conventional RDR malfunctions, blocking the trip signal. Relay issues the trip signal in the case of the proposed algorithm. These results in Figs. 7(c) and 8(c) show the difference between the algorithm suggested in this paper and the conventional algorithm. Table 1 is a comparison of the proposed relaying, RDR, as well as v, and i trend relaying.

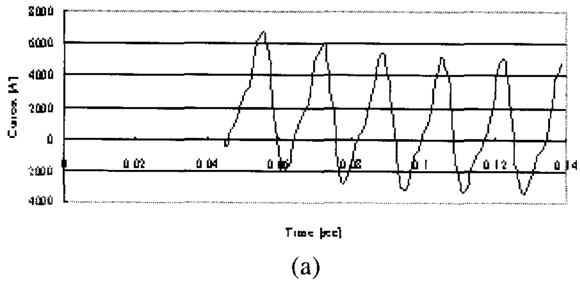


(a)

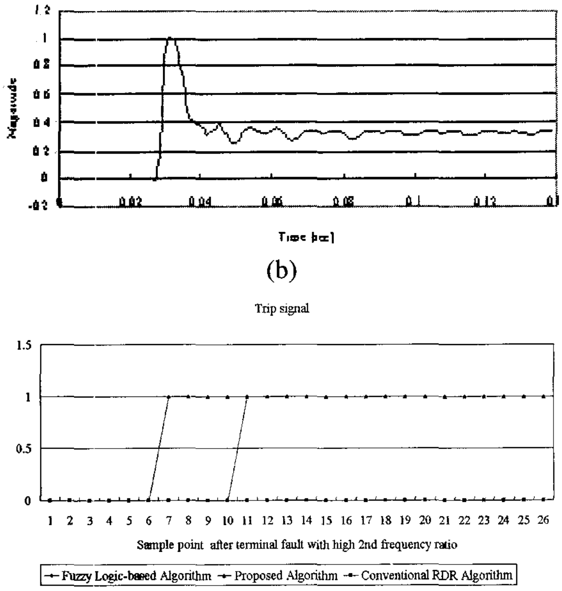
(b)

(c)

Fig. 7 Specific inrush condition (a) A phase current signal in primary side (b) Ratio of 2nd frequency over 1st frequency (c) Trip signals



(a)



(b)

(c)

Fig. 8 Specific terminal to ground fault (a) A phase current signal in primary side (b) Ratio of 2^{nd} frequency over 1^{st} frequency (c) Trip signals

Table 1 Comparison of proposed relaying, RDR, and v, i trend relaying

	Proposed Algorithm	Conventional RDR Algorithm	Voltage and Current Trend Algorithm
Relaying Signal	Terminal Voltage, Current	Current	Terminal Voltage, Current
RDR Usage	Differential	Ratio Differential	Differential
Inrush Discrimination	Differential Current, Wave Shape, 2nd Harmonic Ratio, Flux-Differential Current Slope	2nd Harmonic Ratio	Differential Current, Wave Shape, 2nd Harmonic Ratio
Overexitation Discrimination	Voltage Increase Rate, 5th Har. Change Ratio	5th Harmonic Ratio	Voltage Increase Rate, 5th Har. Change Ratio
Moving Window Length	1 Cycle	1 Cycle	1 Cycle
Digital Filter	DFT	DFT	DFT
Flux-Differential Current Slope Characteristic	Used	Not Used	Not Used
Inrush with Low 2nd harmonics	Operation (Inrush distinction)	False Operation	Operation Not Guaranteed
Internal Fault with high 2nd harmonics	Operation (Fault distinction)	False Operation	Operation Not Guaranteed
Fault Discrimination Time	About 8.34ms	About 33.34ms	About 8.34ms

4. Conclusion

In this paper, a numerical relaying for power transformer protection is developed. The proposed numeric algorithm made use of RMS fluctuation of terminal voltage, instantaneous value of the differential current, RMS changes, harmonic component of differential current, and flux-differential characteristic slope characteristic for overcoming the limits of conventional relaying. The proposed algorithm of utilizing the Turbo C programming language and MS-Excel program could help solve problems related to power transformer protection by examining case studies of data collected by WatATP99 simulation software and MS-Excel. The test results are given as follows.

This study proposed a numerical algorithm that can quickly distinguish between internal faults and magnetizing inrush of the power transformer. The proposed algorithm imported the flux-differential slope characteristic, thus improving and solving the previously existing problems with the conventional 2^{nd} harmonic restraint RDR algorithm. The proposed technique does not solely rely on the inclusion ratio of the 2^{nd} harmonic component when determining the existence of inrush. Because of this, it can prevent malfunction of the RDR by improvements in the iron core material and power system environment changes. The proposed algorithm enables magnetizing inrush detection within nearly 1 cycle and it can detect internal faults within a cycle of 0.5. When compared with the fuzzy relaying, DWT relaying, and conventional RDR relaying algorithm, this new numerical algorithm excelled not only in relay operation time, but also in other comparison criteria.

Acknowledgements

This work was supported by KESRI (R-2003-B-069), which is funded by MOCIE (Ministry of Commerce, Industry and Energy).

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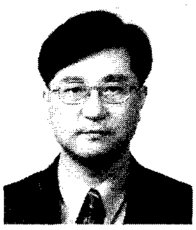

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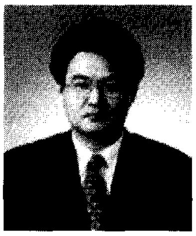

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