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A new method for estimation of time parameters of standard and non-standard switching impulse voltages

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ABSTRACT

In this paper, a new method for estimation of time parameters of standard and non-standard switching impulse voltages is presented. Method is based on estimation of time difference between true and virtual origin of the switching impulse waveform. An analytical expression was derived for calculation of time to peak, which is more accurate than the expression given in IEC 60060-1. The presented method was verified with mathematically generated double-exponential waveforms and waveforms given in IEC 61083-2 with time to peak values within the range 20–300 μs and time to half values within the range 1000–4000 μs. An experimental verification of the proposed method was successfully demonstrated by comparison with an approved impulse voltage measuring system.

1. Introduction

Switching overvoltages (SOVs) in high voltage networks, which are caused by circuit breaker operations, stress the insulation of the high voltage equipment [1]. Therefore, most of high voltage equipment designed for operating voltages above 245 kV should be tested under laboratory simulated switching-impulse voltages [2].

Test requirements along with definitions of standard switching-impulse voltage parameters are given in [3]. The time parameters of standard switching-impulse voltage are shown in Fig. 1. True origin O is an instant where the recorded curve begins a monotonic increase (or decrease for waveforms of negative polarity). Virtual origin O_1 is an intersection of the time axis with a straight line drawn through the reference points A and B in the front. Time to peak T_p is a time interval from the O to the time of maximum value of a switching-impulse voltage, while time to half value T_2 is a time interval between the O and the instant when the voltage has first decreased to half the maximum value. Standard switching-impulse voltage has a T_p of 250 μs and a T_2 of 2500 μs. Acceptable tolerances between specified values and those recorded in laboratory conditions are: ± 20% for T_p, ± 60% for T_2 and ± 3% for value of test voltage. T_p for standard switching-impulse voltages is defined as follows [3]:

$$T_p = K\cdot T_{AB}, \tag{1}$$

where K is a dimensionless value given by:

$$K = 2.42 - 3.08\cdot 10^{-3} T_{AB} + 1.51\cdot 10^{-4} T_2, \tag{2}$$

and T_{AB} is given by:

$$T_{AB} = t_{90} - t_{30}. \tag{3}$$

There are several issues when estimating time parameters of switching impulse voltages. In practice, it is not easy to determine an instant O and time at which maximum of recorded waveform occurs. The reason are oscillations caused by operation of impulse generator around O and noise present in the recorded signal. In the peak area of the impulse there is a problem related to analogue-to-digital conversion which is used for sampling the recorded analogue signal and quantizing its amplitude. Due to this process, the signal values are only available at discrete time intervals. Therefore, the signal amplitude cannot be clearly determined even with high resolution recorder because there can be several discrete points in the peak area often with the same value. Noise could be reduced by averaging the recorded signal, but this affects the parameters of the recorded waveform.

Literature survey showed that only a few papers have been published regarding the issues mentioned above. In [3] it is stated that for non-standard impulses, T_p can be determined by various methods of digital curve fitting dependant on the actual shape. The problem is that there is no guidance on how to determine T_p for non-standard impulses.

The requirements for software used for evaluation of impulse parameters from recorded impulse voltages are given in [4]. It provides test waveforms and reference values for the software required to meet the measuring uncertainties and procedures specified in [3,5–7]. Some

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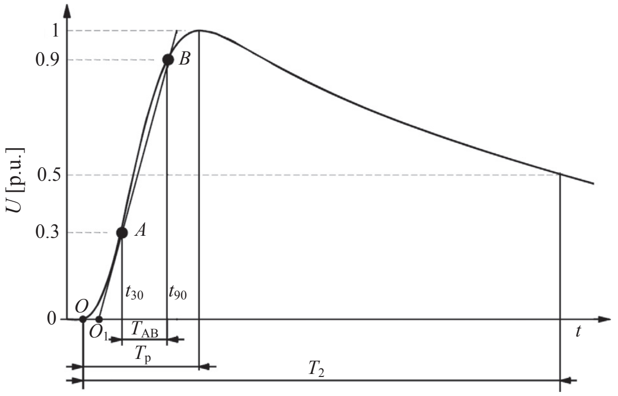


Fig. 1. Standard switching-impulse voltage.

of these waveforms are non-standard with T_p within the range 20–200 µs and T_2 within the range 1000–4000 µs. Expression (1) cannot be applied to all these impulses since it is valid only for standard switching-impulse voltages.

In [8] an impact of lightning and switching impulse definitions on the test results for insulation systems is discussed. The time to peak of a standard switching impulse can be determined more accurately by applying a procedure like the one used for lightning impulses.

In [9] an improved method for evaluation of switching-impulse parameters has been proposed. Similar approach of fitting a double exponential function has already been accepted for lightning impulse voltages and the same algorithm can easily be adapted for T_p evaluation of switching-impulses.

A system for automatic evaluation of voltage impulses according to [3,5] has been described in [10,11]. The results of the validation tests show that in few cases the errors in estimation of switching impulse voltage parameters were higher than the acceptance limit and the errors tends to increase with the noise level.

Therefore, in this paper a new method is proposed for estimation of time parameters of standard and non-standard switching impulse voltages. The main advantage of the proposed method is better accuracy in estimation of switching impulse parameters compared to the expression given in [3].

2. Relation between true origin and other time parameters for double-exponential waveforms

To accurately determine T_p and T_2 it is necessary to know the time instant of true origin *O*. In recorded waveforms, *O* can be masked with oscillations caused by triggering and noise. Therefore, relation of *O* to parameters of the impulse voltage which can easily be determined such as T_{AB} and O_1, was analysed on a group of mathematically generated double-exponential waveforms.

Mathematically generated waveforms were used in the analysis since they have uniquely defined parameters and no noise or oscillations. Switching impulse waveforms were mathematically described by using double-exponential function:

$$u(t) = A\cdot(e^{\alpha t} - e^{\beta t}), \tag{4}$$

where α is negative number specifying falling slope, β is negative number specifying rising slope and *A* is number proportional to the peak value of surge. There is no analytical expression which relates α and β with T_p and T_2 so genetic algorithm (GA) was used to determine α and β for a large number of T_p and T_2 pairs [12]. The flowchart of the algorithm is shown in Fig. 2.

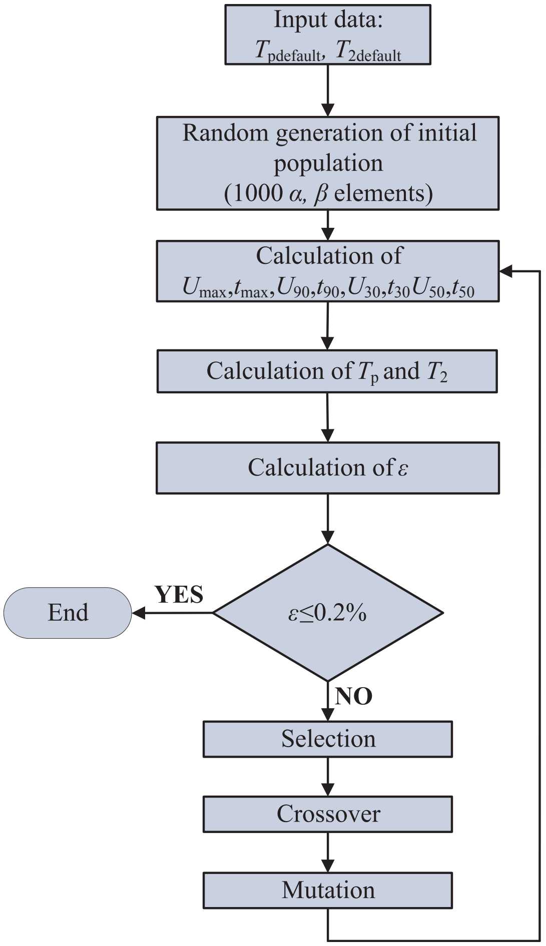


Fig. 2. Flowchart of the algorithm for determination of parameters α and β of the double-exponential function for a given T_p and T_2 pair.

At first, the GA generates a population of parameters α and β. Population size specifies how many individuals there are in each generation (in this case 1000 α and β elements per generation). Initial population is created randomly with a uniform distribution from a predefined range. After the creation of the initial population, T_p, T_2 and fitness function ε are calculated for each α and β element in the initial population. The fitness function ε is the objective function minimized by the GA, which in this case considers the percentage error for each calculated T_p and T_2 regarding known values $T_{pdefault}$ and $T_{2default}$. The fitness function is calculated by using the following expression:

$$\varepsilon = \max\left(\left|\frac{T_p - T_{pdefault}}{T_{pdefault}}\right|, \left|\frac{T_2 - T_{2default}}{T_{2default}}\right|\right)\cdot 100\% \tag{5}$$

Each T_p and T_2 is then rated according to the value of the fitness function. T_p of the switching impulse voltage is obtained by deriving Eq. (4):

$$\frac{du(t)}{dt} = 0. \tag{6}$$

Expression (7) shows the solution of the Eq. (6).

$$T_p = \ln\left(\frac{\alpha}{\beta}\right)\cdot\frac{1}{\beta - \alpha} \tag{7}$$

If the best fitness value is less than or equal to the value of the fitness limit, the algorithm stops. In this case, the fitness limit was set to 0.2%.

For each mathematically generated waveform, time parameters were calculated and a correlation between time difference from *O* to O_1 and T_{AB} value was determined. Computed results are shown in Fig. 3 which shows $O{-}O_1$ time difference versus T_{AB} with T_p and T_2 as parameters.

It can be noticed that family of curves can be well approximated with a straight line. A linear dependence between T_{AB} and $O{-}O_1$ time

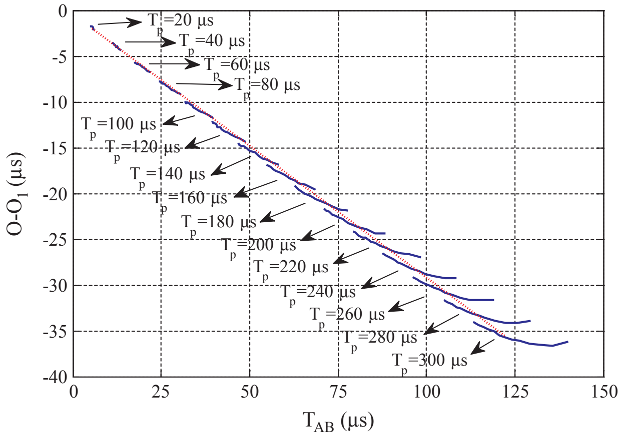


Fig. 3. *O*-O_1 time difference versus T_{AB} with T_p and T_2 as parameters varied from 20 to 300 µs and 1000 to 4000 µs, respectively.

difference between is marked with red dotted line in Fig. 3. An analytical expression (8) describes this linear dependence:

$$O{-}O_1 = -0.29006\cdot(T_{AB}{-}5.1){-}1.715. \tag{8}$$

With (8), parameter *O* of switching impulse waveform can be determined directly, since O_1 and T_{AB} can easily be found.

3. A new analytical expression for estimation of T_p

When parameter *O* is known, T_p and T_2 can be easily determined. Previously described waveforms were used to obtain a relationship between T_p and T_{AB} for T_2 values ranging from 1000 µs to 4000 µs. Computed results are shown in Fig. 4.

From computed results, the following analytical expression (9) is derived:

$$T_p = A\cdot T_{AB}^{B} + C, \tag{9}$$

where *A*, *B*, and *C* are parameters given by:

$$A = 23.76\cdot T_2^{0.02928}{-}25.13, \tag{10}$$

$$B = 2.983\cdot T_2^{-0.6853} + 0.8484, \tag{11}$$

$$C = 98.66\cdot T_2^{-0.01173}{-}90.05. \tag{12}$$

Expressions (10)–(12) were derived by fitting calculated results in Figs. 5–7 showing the dependence between parameters *A*, *B*, *C* and T_2 value.

Expression (9) is proposed for estimation of T_p for both standard and non-standard switching impulse voltages.

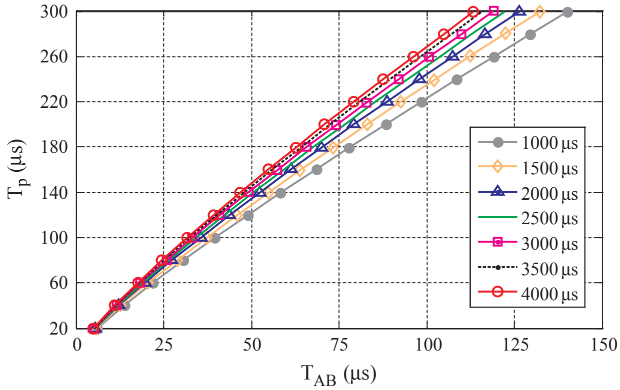


Fig. 4. T_p versus T_{AB} with T_2 as a parameter varied from 1000 to 4000 µs.

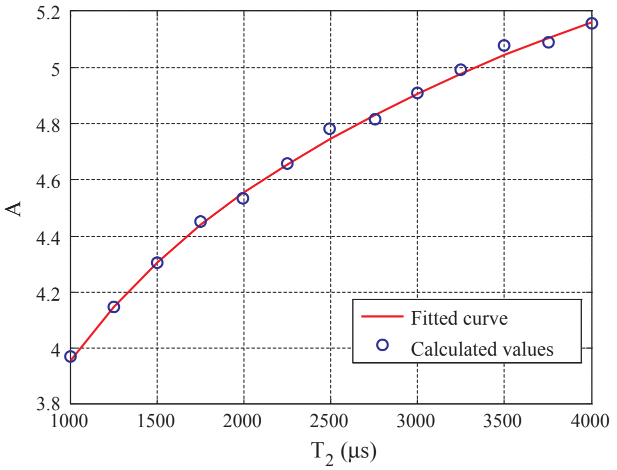


Fig. 5. Dependence between parameter *A* and T_2.

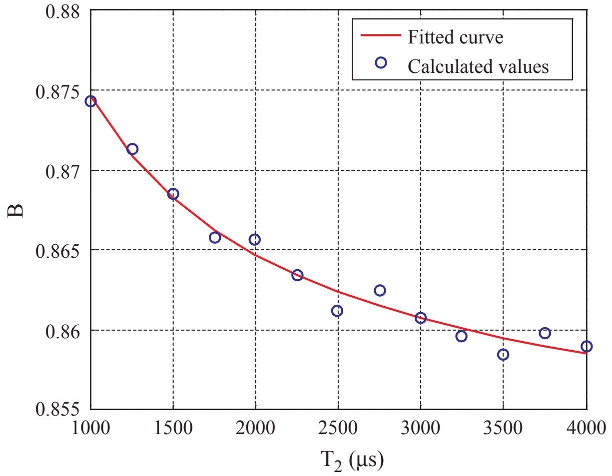


Fig. 6. Dependence between parameter *B* and T_2.

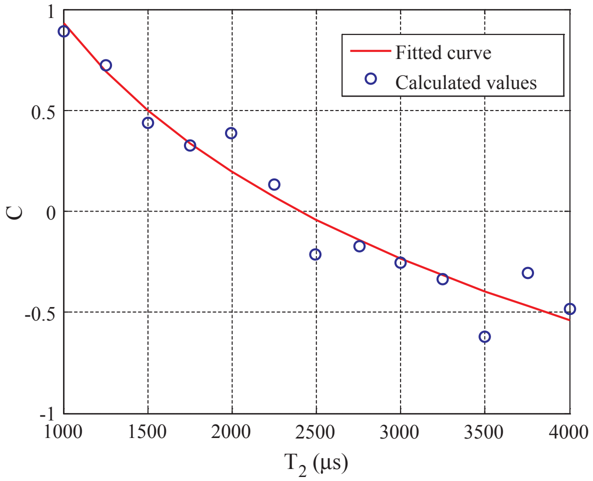


Fig. 7. Dependence between parameter *C* and T_2.

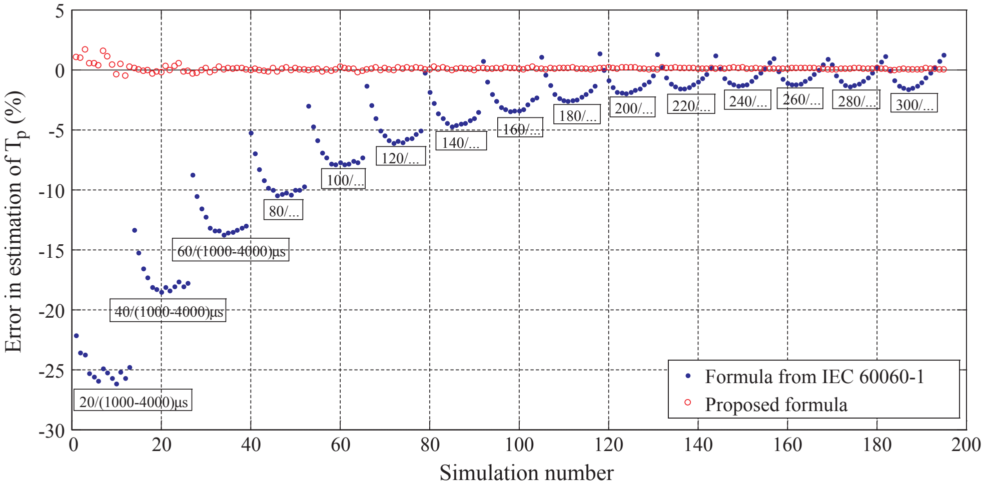


Fig. 8. Errors in estimating T_p by using expression from IEC 60060-1 and by applying the proposed formula.

Table 1
Reference curves given in [4].

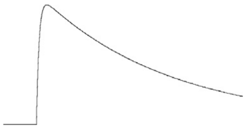
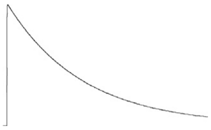
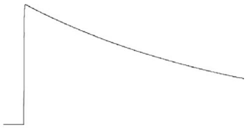
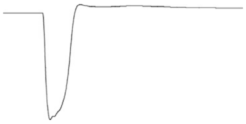
Designation of reference curve	Reference impulse	Description
SI-A1		Switching impulse, 250/2500 µs
SI-A2		Switching impulse, 20/1300 µs
SI-A3		Switching impulse, 43/4000 µs
SI-M1		Measured during transformer test
SI-M2		Measured switching impulse

Table 2
Reference values and calculated values of U_p.

Reference curve	Reference value (kV)	Acceptance limit (%) of U_p	Proposed method (kV)	Deviation (%)
SI-A1	950.28	± 0.1	950.2320	0.0051
SI-A2	0.9877	± 0.1	0.9877	0.0009
SI-A3	99.2190	± 0.1	99.2186	0.0004
SI-M1	−0.5907	± 0.5	−0.5913	0.0991
SI-M2	3.6800	± 0.5	3.6721	0.2142

Table 3
Reference values and calculated values of T_p.

Reference curve	Reference value (µs)	Acceptance limit (%) of T_p	Proposed method (µs)	Deviation (%)
SI-A1	250.7	± 2	252.2753	0.6284
SI-A2	19.89	± 2	20.2332	1.7253
SI-A3	43.08	± 2	43.2923	0.4927
SI-M1	186.6	± 5	178.9806	4.0833
SI-M2	218.0	± 5	221.1699	1.4541

Table 4
Reference values and calculated values of T_2.

Reference curve	Reference value (µs)	Acceptance limit (%) of T_2	Proposed method (µs)	Deviation (%)
SI-A1	2512	± 2	2512.2	0.0079
SI-A2	1321	± 2	1319.8	0.0937
SI-A3	3987	± 2	3986.1	0.0229
SI-M1	655	± 2	646.9806	1.2243
SI-M2	2407	± 2	2447.3	1.6724

4. Verification of the proposed method for estimation of time parameters of switching impulse voltages

4.1. Computational verification with mathematically generated double-exponential waveforms

Accuracy of the proposed expression (9) was compared to the expression (1) from [3]. Expressions were applied to a set of mathematically generated double-exponential waveforms with known parameters and errors were calculated according to (13).

$$Error\,(\%) = \frac{T_{p\,estimated} - T_p}{T_p} \cdot 100\,\%, \tag{13}$$

A total of 195 simulations were performed covering waveforms with T_p within the range 20–300 µs and T_2 within the range 1000–4000 µs. Errors in determining T_p are shown in Fig. 8. The highest error for proposed expression is 1.7% for all considered switching impulse waveforms, while according to expression (1) the highest error is −26.2%. Errors are significantly lower when using the proposed expression for both standard and non-standard waveforms. Therefore, the proposed expressions (9)–(12) can be applied for estimating T_p.

Table 5
Comparison of proposed method and expression (1) according to [3], with an approved commercial impulse voltage measuring system.

Impulse number	Parameters of impulse voltage	Approved impulse voltage measuring	Proposed method	Deviation of proposed method (%)	Expression (1) according to [3]	Deviation of expression (1) (%)
1	U_p (kV)	−437.294	−437.6357	0.08	–	–
	T_p (μs)	269.465	274.2435	1.77	275.6241	2.29
	T_2 (μs)	3745	3744.2761	−0.02	–	–
2	U_p (kV)	−850.577	−851.3805	0.09	–	–
	T_p (μs)	275.005	281.5977	2.40	283.5674	3.11
	T_2 (μs)	3807	3812.2795	0.14	–	–
3	U_p (kV)	526.642	527.1405	0.09	–	–
	T_p (μs)	267.035	271.8599	1.81	271.1844	1.55
	T_2 (μs)	3343	3344.6102	0.05	–	–
4	U_p (kV)	1055	1055.8488	0.08	–	–
	T_p (μs)	270.533	275.0530	1.67	274.5112	1.47
	T_2 (μs)	3358	3362.6802	0.14	–	–

4.2. Testing and verification of the proposed method with waveforms from IEC 61083-2

The proposed method was tested against reference curves presented in [4] to check if it fulfils the requirements for software used for evaluation of impulse parameters from recorded impulse voltages. Curves consist of different impulse voltages and reference values for the impulse parameters such as peak value U_p, T_p and T_2. These impulses shall be processed by the software under test, and the parameters evaluated from the processed data shall match with the reference values.

Proposed method was verified with five reference switching-impulse curves shown in Table 1, which contain not only double exponential curves, but also measured ones obtained by during high-voltage testing.

Parameters of these five curves were determined by applying the proposed expression (9). Computed results are shown are in Tables 2–4 and they are compared to the reference values and acceptance limits given in [4].

It was shown in [9] that expression (1) gives T_p values for reference curves SI-A2 and SI-A3 which are outside the acceptance limits. Computed results show that deviations of amplitude and time parameters obtained with proposed expression are within acceptance limits given in [4]. This means that the proposed approach fulfils the requirements for software used for evaluation of impulse parameters from recorded impulse voltage.

4.3. Experimental verification

Experimental verification was performed by comparing the results obtained with proposed method and expression (1) according to [3], with the ones obtained by an approved impulse voltage measuring system (commercial transient recorder from well-known manufacturer which is in use for decades). Four different switching impulse voltages obtained by an approved impulse voltage measuring system were used for testing the proposed method. Switching impulses were recorded during testing of inductive and capacitive voltage transformers. Comparison of results is shown in Table 5.

Results of both time and amplitude parameters obtained by proposed method coincide well with the ones from an approved impulse voltage measuring system. Since recorded switching impulse voltages are standard ones, both the proposed method and expression (1) according to [3] give satisfying results in estimation of T_p, as expected.

5. Conclusion

A new method is presented for estimation of time parameters of standard and non-standard switching impulse voltages. An extensive analysis was performed to determine the relation between the true origin and other time parameters for mathematically generated double-exponential waveforms. From the obtained results, an analytical expression was derived for calculation of T_p, which is more accurate than the expression given in [3].

Computational verification with mathematically generated double-exponential waveforms showed that errors in estimation of T_p are significantly lower when using the proposed expression for both standard and non-standard waveforms. Proposed method gives highest error of 1.7% in determining T_p for mathematically generated standard and non-standard switching impulse voltages, while according to [3] the highest error is −26.2%.

The proposed method was tested against reference curves given in [4] and computed results show that deviations of amplitude and time parameters obtained with proposed expression are within acceptance limits. Expression from [3] gives T_p values which are outside the acceptance limits for certain reference curves.

An experimental verification was successfully performed by comparing the results obtained by proposed method with the ones from an approved impulse voltage measuring system. Highest deviation of the results obtained by proposed method from the ones obtained by an approved commercial impulse voltage measuring system is 2.4% for standard waveforms.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijepes.2017.10.001.

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