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Research on application of FDNE based on RTDS and comparison analysis of fault transient of Shanghai Sijing power grid

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Zou Xiaofeng[1] ✉, *Yang Shihao*[2], *Zhou Desheng*[1], *Song Jie*[1]

[1]*Department of Power Grid Technology, Shanghai Electric Power Research Institute, Shanghai, People's Republic of China*
[2]*Department of Equipment Maintenance, State Grid Shanghai Municipal Electric Power Company, Shanghai, People's Republic of China*
✉ *E-mail: unisamuel@hotmail.com*

Abstract: As a most widely applied real-time digital simulation system, real time digital simulation (RTDS) is however quite limited on scale of simulation by the number of hardware purchased. Through frequency-dependent network equivalent (FDNE), scale of simulation of RTDS could be largely increased by frequency equivalent on limited hardware. Based on basic principles of FDNE, function limitations and problem are analysed, taking the Shanghai Sijing district power grid as an example; detailed simulation model and FDNE equivalent module are built, transient characteristics under faults before and after FDNE equivalent are analysed. Furthermore, the fault characteristics of high-voltage direct current (HVDC)-Sijing power grid is also studied, which provides a realistic means for real-time digital simulation of AC–HVDC hybrid power grid with limited hardware of RTDS.

1 Introduction

Real Time Digital Simulation (RTDS) is a most widely used real-time digital simulation system. The real-time simulation is based on wave characteristics of transmission line, where the power system could be divided into several parts for parallel computing. Thus calculation of equivalent matrix of power grid can be completed in a small time step. Real-time simulation can be used for testing logic functions of secondary devices like AC relay protection and high-voltage direct current (HVDC) control protection. However, since RTDS calculates node voltage of system through network algorithm, the maximum number of system nodes that can be calculated in a rack is limited by its maximum computational capabilities. Therefore, the scale of the grid simulated can only be increased by the increase of numbers of racks (calculation module) in RTDS.

Under this background, in order to meet the growing demand for large-scale power grid simulation, RTDS proposed a wide-band network equivalent algorithm named frequency-dependent network equivalent (FDNE). Through equivalent of the non-core region of the large power grid, the scale of simulation can be increased under the same RTDS hardware, which is of great significance to the real-time digital simulation of large-scale regional power grids like east China power grid.

2 Basic principles of FDNE

FDNE is a wide-band multi-port equivalent algorithm that provides the possibility of simulating a larger system with the same RTDS hardware on a reasonable simplification [1–4]. The basic principles are shown in Fig. 1.

The whole system is divided into internal and external systems, and the three-phase bus is called boundary bus. The internal system is represented in a detailed model in RTDS; the external system uses the equivalent simplified model of FDNE, which consists of two parts:

(a) Frequency-dependent network equivalent branch (FDNE). Used to represent the electromagnetic transient (EMT) process in external system. It uses a rational function of the s domain to fit the admittance (matrix) of the external system at a given frequency interval at the boundary. However, during the acquisition of frequency response, all non-linear characteristics (including switches and faults) in external system, and all non-boundary buses are ignored.

(b) Dynamic equivalent branch. Used to represent the electromechanical transient process in the system. Using a Norton equivalent current source controlled by the transient stability analysis (TSA) module in RTDS to simulate the dynamic frequency characteristics of the external system and feed it back into the EMT electromagnetic transient calculation. The TSA algorithm only takes into account the positive frequency component of base frequency, ignoring the negative sequence, the zero sequence and the high-frequency component. Where the network equation module and the dynamic components such as generators can be calculated in parallel, so as to ensure the real-time performance of equivalent components.

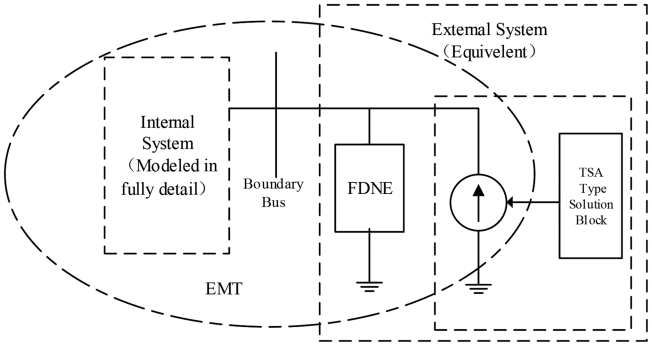


Fig. 1 *Basic Principles of FDNE*

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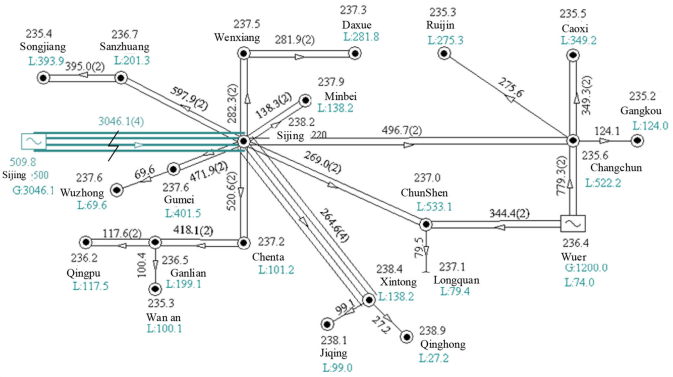


Fig. 2 *Geographical wiring of Shanghai Sijing power grid*

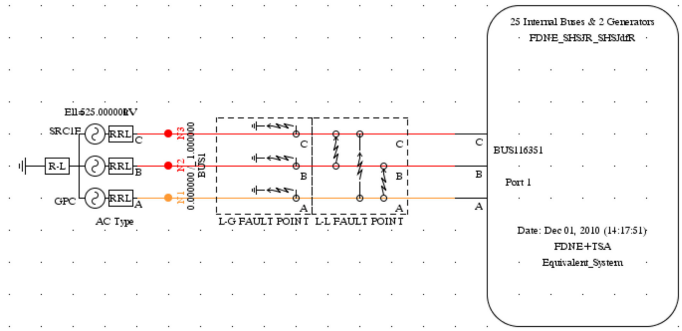


Fig. 3 *FDNE equivalent of Sijing power grid*

The FDNE branch and TSA equivalent branch are combined together, collectively referred to as FDNE equivalent.

3 Limitations and problems of FDNE

3.1 Limitations of FDNE

(a) The equivalent system is linear. Switch operation is not allowed in FDNE. Saturation of transformers and generators are ignored. No HVDC and other power electronic devices. It is best to use components that have been tested for FDNE equivalent to build an external system which are placed under 'FDNE Ready' tab of the components library.

(b) Zero sequence impedance and positive sequence impedance are equal.

(c) No more than three boundary buses.

(d) FDNE contains up to 100 buses (including boundary bus).

(e) Does not support 3PC card.

3.2 Problems of FDNE

(a) When FDNE equivalent module is connected to the external system, A, B, and C phases are reversed by default.

(b) Using the same FDNE equivalent component, compared to those of old RSCAD software version, simulation results of the RSCAD with FDNE function are closer to the detailed model. When using FDNE, it is recommended to use the latest RSCAD version.

(c) The equivalent spectral response in the mpb file is exactly the same as the original spectrum, while the high-frequency response of those in FDNE sample are different.

4 FDNE case analysis of Sijing grid

The geographical wiring of Sijing power grid is shown in Fig. 2.

FDNE equivalent is made for Sijing power grid (not including infinite 500 kV voltage source) and shown in Fig. 3. The active power absorbed by Sijing power grid at steady state before and after FDNE equivalent are 3038.4 and 3055.7 MW, reactive power are 713.9 and 729.2 MVar. The steady-state errors of active and reactive power were 0.569 and 2.136%, respectively.

4.1 0.1 s three-phase short-circuit fault

A 0.1 s three-phase short-circuit fault is applied at 500 kV busbar. The A-phase short-circuit current of the fault spot, node voltage of the boundary bus 116,351 and power generated by infinite system before and after FDNE equivalent are compared in Fig. 4, where red and blue are before and after equivalent, respectively.

It can be seen that the short-circuit current before and after the equivalent is well consistent, and the error of the active power, the reactive power and the node voltage are concentrated in the transient process after the fault disappears and gradually converge. In the detailed system without equivalent, oscillation occurs in the node voltage of faulted phase after fault which contains 10,000 Hz high-frequency harmonics. However, since the highest frequency of FDNE fitting is set to 1200 Hz, the node voltage with FDNE equivalent does not produce high-frequency oscillation.

Note that the lock/free switch of generators in RTDS runtime should be pulled out and set free, otherwise the generator will always be at the ideal state of constant speed.

4.2 0.1 s single-phase ground fault

A 0.1 s A-phase ground fault is applied at the same place.

The A-phase short-circuit current of the fault spot, the node voltage of the boundary bus and power generated by infinite system before and after FDNE equivalent are compared in Fig. 5.

5 FDNE case analysis of HVDC-sijing

When using RTDS to test HVDC control and protection devices, large external AC power grid brings pressure to RTDS hardware. Therefore, accuracy of FDNE equivalent of external AC power grid has a great significance for simulation test of HVDC system.

Based on the RTDS model of ±500 kV Longquan–Zhengping HVDC system, a HVDC transmission line is placed between the infinite system and the Sijing power grid. Rated HVDC current is 3 kA, rated power 3000 MW, length of HVDC transmission line 1060 km, both converter stations are dual 12-pulse bipolar structure, including AC and HVDC filter group.

The short-circuit current of the infinite system SRC1 is set to 30 kA. Since the Sijing power grid is weak system, in order to support the AC voltage of inverter side of HVDC, an ideal voltage

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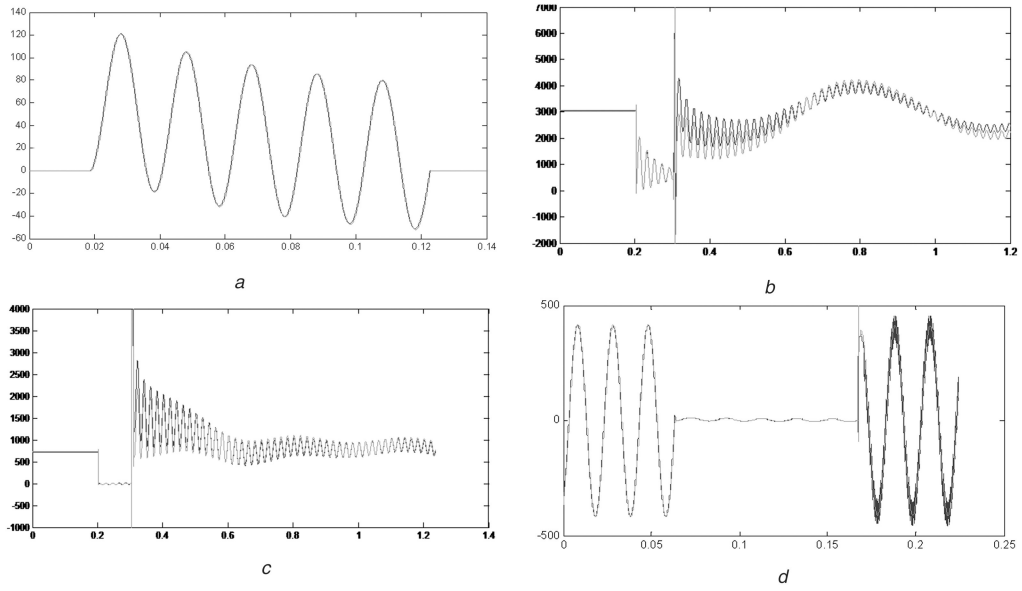


Fig. 4 *Comparison of simulation of 0.1 s three-phase short-circuit fault before and after equivalent, (Red – before FDNE, Blue – after FDNE)*
(a) A-phase short-circuit current, ***(b)*** Active power of infinite system, ***(c)*** Reactive power of infinite system, ***(d)*** A-phase voltage of boundary bus

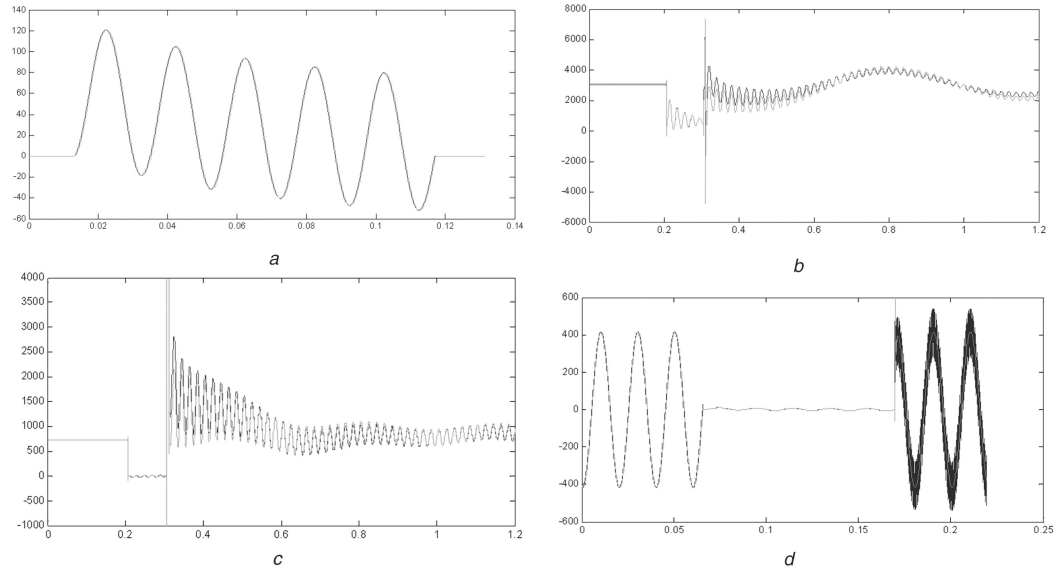


Fig. 5 *Comparison of simulation of 0.1 s single-phase ground fault before and after equivalent, (Red – before FDNE, Blue – after FDNE)*
(a) A-phase short-circuit current, ***(b)*** Active power of infinite system, ***(c)*** Reactive power of infinite system, ***(d)*** A-phase voltage of boundary bus

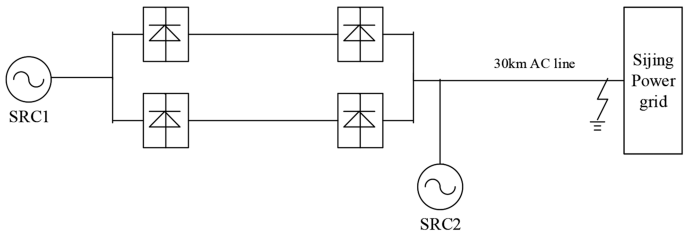


Fig. 6 *System of HVDC-Sijing power grid*

source SRC2 is connected in parallel between HVDC and Sijing power grid where the initial active power is 300 MW; the system is shown in Fig. 6.

Before equivalent, due to the large size of detailed model for the AC system, the SRC1, SRC2 and HVDC lines are placed in rack1, the detailed model of the Sijing power grid is calculated in rack2 and rack3, and a typical 30 km AC transmission line is placed between HVDC and AC system for the need of parallel computing of RTDS.

After equivalent, FDNE module of the whole Sijing power grid and HVDC system can be calculated in a single rack, but for consistency of the simulation before and after the equivalent, the 30 km AC line remained.

HVDC control strategy: the rectifier side (infinite system) using constant current control, inverter side (Sijing power grid) using constant extinction-angle control. While stabilising the HVDC system, it is found that the system is quite different before and after the equivalent. For the system before equivalent, SRC1 takes short-circuit current of more than 45 kA to stabilise HVDC system. However for the system after equivalent, HVDC can be stable with only 30 kA SRC1 short-circuit current. Thus the following comparisons of simulation are all based on fault current of 45 kA.

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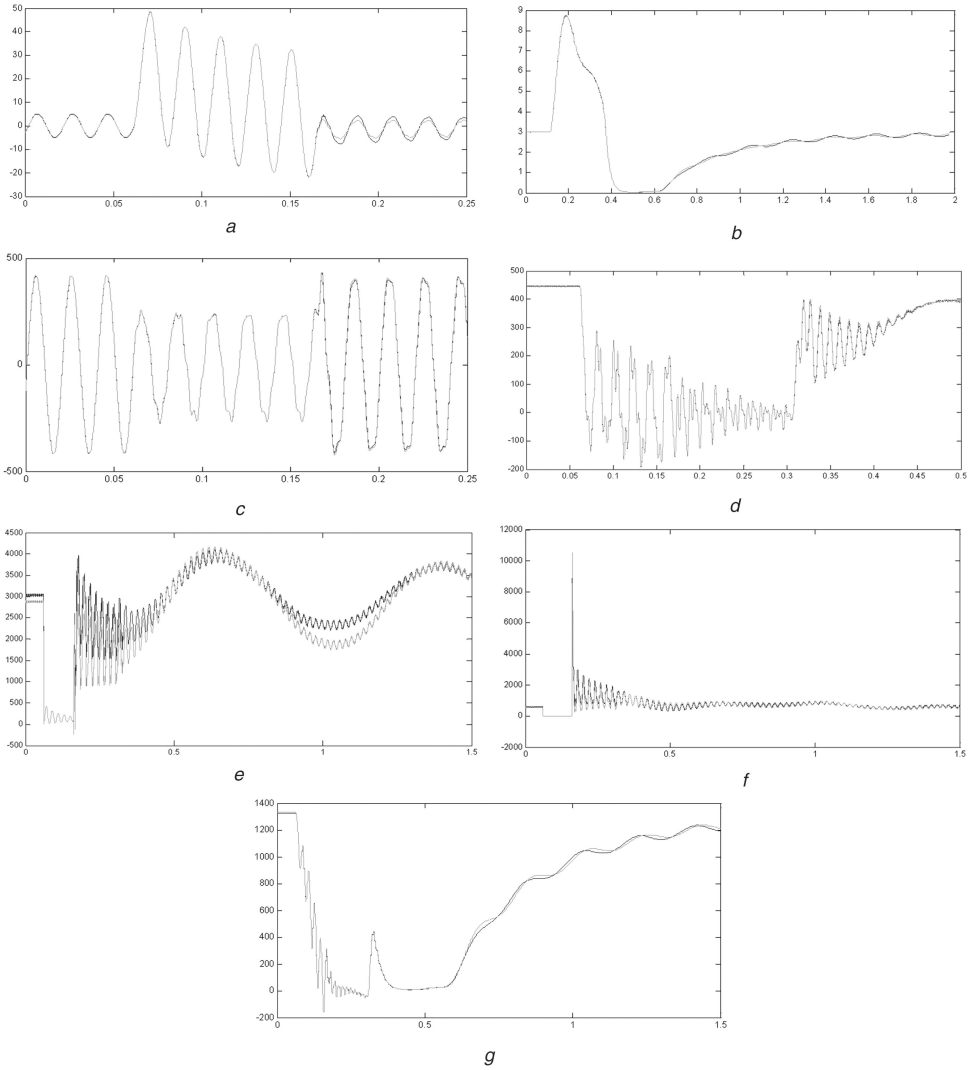


Fig. 7 *Comparison of simulation of 0.1 s three-phase short-circuit fault of HVDC-Sijing power grid before and after equivalent, (Red – before FDNE, Blue – after FDNE)*

(a) A-phase current at fault spot, ***(b)*** HVDC current of polar *I*, ***(c)*** A-phase voltage at fault spot, ***(d)*** HVDC voltage of polar *I*, ***(e)*** Active power absorbed by Sijing power grid, ***(f)*** Reactive power absorbed by Sijing grid, ***(g)*** Power transmitted by HVDC line of polar *I*

5.1 0.1 s three-phase short-circuit fault

A 0.1 s three-phase short-circuit fault is still applied at 500 kV busbar.

The A-phase short-circuit current, the node voltage, active power and reactive power before and after FDNE equivalent are compared in Fig. 7.

As the HVDC converter valves work, the system has been in a continuous on and off state, therefore the fault process contains more high-frequency components, and the transient process is more complex. It can be seen from Fig. 7 that compared with the detailed system model, the transient process during and after fault of FDNE equivalent system is basically the same. However, the active power absorbed by Sijing power grid in a steady state and after fault has some difference. The difference between the characteristics of the FDNE equivalent system and the original Sijing power grid is very small, which brings a foundation for further application.

5.2 0.1 s single-phase ground fault

A 0.1 s A-phase ground fault is applied at the Sijing power grid side. The comparison of simulation is shown in Fig. 8.

The results and analysis of simulation are similar to those of 0.1 s three-phase short-circuit fault.

6 Conclusion

RTDS is currently a most accepted real-time digital simulation system, which is widely used in testing of interaction of secondary devices and primary power system. However, its development has been limited by the direct association of simulation scale and the number of simulating hardware which bears a relatively high price.

RTDS-based FDNE wide-band multi-port equivalent can greatly increase the scale of power grid simulated with limited computing hardware. The transient characteristics in various faults of FDNE module and detailed system are relatively close, which lays the foundation for simulation test of large-scale regional power grid like East China Power Grid. At the same time, through partial equivalent of the AC power system, it provides a realistic means for the deep analysis of the fault characteristics of HVDC control and protection system under the AC–HVDC hybrid power system.

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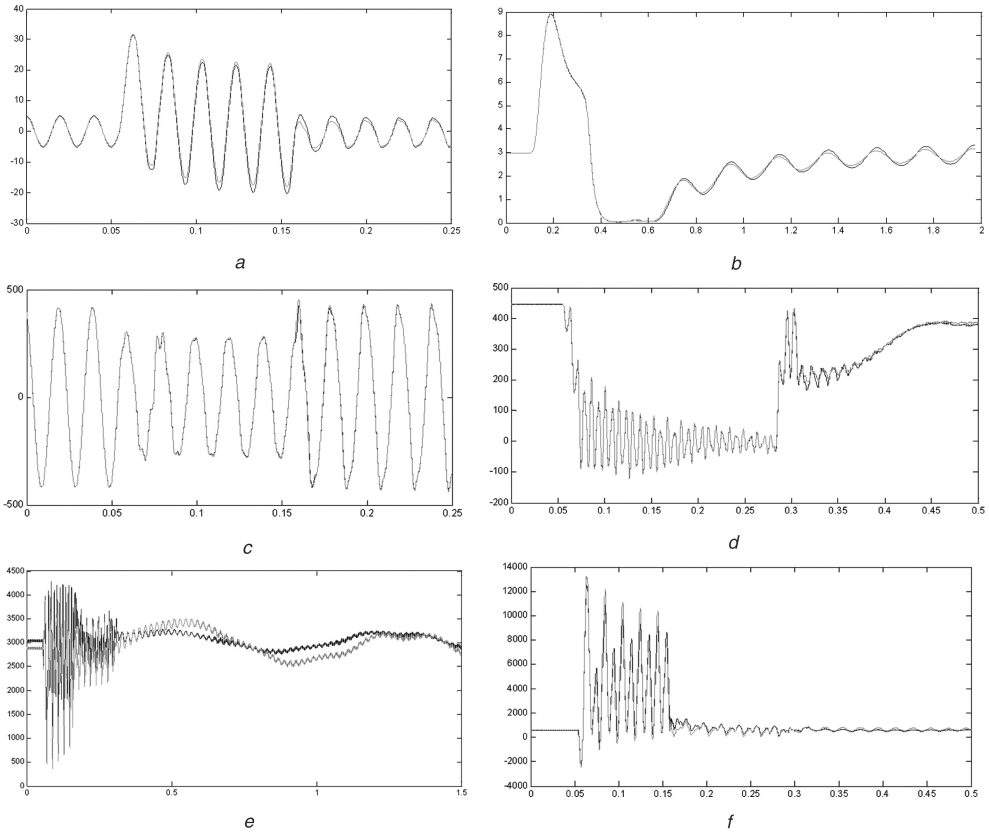


Fig. 8 *Comparison of simulation of 0.1 s single-phase ground fault of HVDC-Sijing power grid before and after equivalent, (Red – before FDNE, Blue – after FDNE)*

(a) A-phase current at fault spot, ***(b)*** HVDC current of polar *I*, ***(c)*** A-phase voltage at fault spot, ***(d)*** HVDC voltage of polar *I*, ***(e)*** Active power absorbed by Sijing power grid, ***(f)*** Reactive power absorbed by Sijing power grid

7 Reference

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