STATIC AND DYNAMIC REDUCTION OF LARGE SYSTEMS

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Abstract - **Issues on the establishment of equivalent networks are becoming essential for the deregulated power market. This paper presents a comprehensive tool for network reduction of large power systems. Through integrating different methodologies into a simulation program, static and dynamic network reductions can be performed by adopting one common database. With a readily integrated identification module, network reduction can be carried out under the static conditions either in the time domain or in the frequency domain. In addition, also the dynamic network reduction can be performed by means of this identification module. Furthermore, a novel module for automatic dynamic reduction in the simulation program is presented which is based on non-linear models using the cross correlation technique realized in the time domain. Two case studies for two individual real power systems are presented in this paper as examples. The results achieved validate the functionality of the program for network reduction.**

Keywords: Static network reduction, dynamic network reduction, clusters, cross correlation, white-noise signal, identification and simulation program

I. INTRODUCTION

Deregulation and privatization in the power market are significantly changing relations among power generation, transmission system and distribution. Utilities, especially, transco companies are faced to be oriented in a competitive market environment not only to maximize their profits. They are also trying to achieve a marketshare as high as possible. In this new situation, exchanges of detailed network data among neighbor competitive transcos are becoming difficult. However, with enhanced stability requirements, the dynamic behavior of the interconnected power systems involved need to be more carefully studied online and offline. This includes studies such as overall system stability, dynamic security assessment and coordinating system controls in a global manner, etc. Thus, issues on the establishment of equivalent networks for a large, multi-owner's interconnected power system become essential.

On the other hand, in power system analysis, it is also a common practice to represent the parts of a large interconnected power system by some form of a reduced order equivalent model. Depending on different applications, such as Transient Network Analysis (TNA) or Real-Time-Digital-Simulator (RTDS) studies, fundamental frequency overvoltage studies and AC filter performance calculations, equivalent models can be established either by static or dynamic network reduction.

The motivation of this paper is to provide a comprehensive tool for reducing the order of large and very large power systems. The significant feature of this tool is the performance of network reductions at steady state and dynamic conditions only with one simulation program using a common database. Once the full system models are established with the simulation program, they can be adopted to derive either a static equivalent model or a dynamic one or both of them.

Two methodologies of network reductions being available in the simulation program NETOMAC® are described in this paper: an identification method and a novel method for automatic dynamic network reductions. The identification module can be used for static and dynamic network reductions, while the method for automatic dynamic reductions, which has been newly developed and differs from existing algorithms, is more efficient for establishing dynamic equivalent models with an enhanced accuracy.

An additional advantage of this tool is its simplicity in the verification of results. There is no need to convert the reduced network data from the program with which the reduction is performed to another simulation program to check the reduction. Once the reduction process is finished, the simulation of the reduced network can be performed with the same program. With the help of various analysis modules available in the program, the verification can be carried out in the time and frequency domain. In addition, the verification can also be performed with the eigenvalue module to compare the oscillation modes of the full and the reduced system.

This paper is focused on dynamic network reductions with a simulation program. Two case studies are demonstrated based on real power systems as application examples. The fist case study is to establish an equivalent model of a large power pool where the power generated is transmitted to a load center by means of HVDC. This equivalent model is established for RTDS studies by using the identification module of the program. The second application performs a dynamic reduction of a large interconnected power system using the automatic module newly developed. The results of two case studies validate the efficiency of the tool presented as modules in the simulation program for the power system reduction in engineering applications.

II. METHODS FOR NETWORK REDUCTIONS

Dynamic reductions of large power systems are typically performed in three steps. In the first step, coherent generators are identified using algorithms such as linear simulations [3] and slow coherency [4]. In the second step, equivalent generators are aggregated for each coherent group of generators, while the respecting passive network is constructed in the third step. Previously, various approaches for network reductions have been proposed [5][6][7]. These proposals are typically based on the linearization of the system involved and not integrated into a simulation program. Thus, they require data converting from/to a simulation program for receiving the established operating point and for verifying the results. In addition, linear methods cannot properly capture complex dynamics of the system, especially during critical faults (major disturbances). This could present difficulties for reducing the orders of the non-linear models in that the equivalent established to provide desired performance at a small signal condition might not guarantee acceptable performance in the event of major disturbances.

A. Simulation Program

A complex non-linear model of a power system can be described in a set of differential-algebraic equations by assembling the models for each generator, load and other devices such as controls in the system, and connecting them appropriately via the network algebraic equations. These differential-algebraic equations of a non-linear power system are given as

$$\begin{aligned} \dot{x} &= f(x,z,u) \\ 0 &= g(x,z,u) \\ y &= h(x,z) \end{aligned} \qquad (1)$$

where x is the state, z is a vector of algebraic variables, u is the input vector, y is the output vector and f, g, h are non-linear functions. To describe such a non-linear power system, the simulation program NETOMAC [1] is adopted in which the system of differential equations are transformed into sets of algebraic equations solved by using the well known trapezoidal rule. NETOMAC (Network Torsion Machine Control) is a simulation program system used widely for the simulation of electromechanical and electromagnetic transient phenomena as well as steady-state behavior of a power system.

It provides a frequency analysis module with the FFT technique and an eigenvalue analysis module in the frequency domain. In addition, it integrates also an optimization/identification mode [2] for solving various optimization tasks and parameters identification programs. Recently a novel method for automatic dynamic network reduction has been integrated into the program. The main benefit of the program is that such a wide field of applications uses only one surface and one database without data converting among the modules.

B. Semi-Automatic Procedure

The semi-automatic procedure is based on the identification algorithm adopting a modified "Least-Square" technique [2]. The basic approach of the algorithm is described as follows:

$$\min f(x) = \sum_{i=1}^{m} \{ F_{org\,i}(x) - F_{eq\,i}(x) \}^2 = E^T E \,, \qquad (2)$$
$$\text{subject to}: x_{low} \le x \le x_{upp}$$

where x_{low} and x_{upp} ($x \in \Re^n$) are the parameter lower and upper limits, $F_{org\,i}(x)$ denotes the i-th state variables (i=1, ..., m) of the original system which are supposed as the known values, $F_{eq\,i}(x)$ denotes the i-th corresponding state variables (i=1, ..., m) of the reduced system that can be represented by Taylor first order derivations of $F_{eq\,i}(x)$ at x_k

$$F_{eq\,i}(x) = F_{eq\,i}(x_k) + \sum_{j=1}^{n} \frac{\partial F_{eq\,i}}{\partial x_j}\Big|_{x_k} \Delta x_j \qquad (i = 1,\ldots,m). \qquad (3)$$

The equation (3) can be expressed in a compact form

$$F_{eq}(x) = F_{eq}(x_k) + F\big|_{x_k} \Delta x \,, \qquad (4)$$

with the vector $F_{eq}(x)$ and the Jacobian matrix $F^{(n,m)} = F\big|_{x_k}$ at x_k. The necessary condition for the optimal solution of $f(x)$ (2) is then given

$$\frac{\partial f(x)}{\partial \Delta x_j} = 0 \,. \qquad (5)$$

By inserting equation (3) into equation (2), the well-known Gauss Equation is deduced at the condition (5)

$$F^T F \Delta x = F^T E \,. \qquad (6)$$

From (6), the optimal parameter set x can be determined iteratively by calculating

$$x_{k+1} = x_k + \left(F^T F\right)^{-1} F^T E \,, \qquad (7)$$

to meet the convergence condition

$$f(x_{k+1}) \le f(x_k) \,. \qquad (8)$$

The iterative minimization of (2) continues until predefined criteria are satisfied. As a modification to "Least-Square" algorithm, a special treatment is proposed for dealing with the linear dependent components in the matrix $F^T F$, so that the convergence of the procedure is ensured [2].

For static network reductions, two steps are needed: reduction of passive network, in which all generators are replaced by the corresponding voltage sources, and determination of the short circuit capacity. Also two steps are necessary for dynamic network reductions: passive network reduction and establishing equivalent generators with determining parameters of each individual equivalent generator. Passive network reductions are performed with a special module in the simulation program, where the corresponding load flows remain unchanged. A passive equivalent model can also be established manually to meet some special requirements, such as setting up an equivalent for fundamental frequency overvoltage studies or an equivalent for harmonics studies. The determination of the short circuit capacities and the determination of equivalent generators or other system parameters are carried out by using the identification module, whereas the corresponding equivalent controllers such as exciters and governors can also be identified.

$$\min f = \int_{t=0}^{t} \sum_{i=1}^{k} \left\{ \left(\frac{P_{org,i}(t) - P_{eq,i}(t)}{P_{org,i}(t)} \right)^2 + \left(\frac{Q_{org,i}(t) - Q_{eq,i}(t)}{Q_{org,i}(t)} \right)^2 + \left(\frac{V_{org,i}(t) - V_{eq,i}(t)}{V_{org,i}(t)} \right)^2 + \left(\frac{\theta_{org,i}(t) - \theta_{eq,i}(t)}{\theta_{org,i}(t)} \right)^2 \right\} \quad (9)$$

The key issue for solving these two problems is the formulation of proper target functions. By using the identification algorithm described from equation (2) to equation (8), parameters of individual equivalent generators and other selected controller parameters are determined at the minimum of the target function to obtain performances, which are similar to that of the original system. Parameters to be determined for dynamic reductions are mainly controller parameters, such as gains and time constants, and generator parameters.

An interconnected power system to be reduced consists of three subsystems: neighbor system, subsystem remaining unchanged and subsystem to be reduced. State variables on the tie lines (i = 1,..., k) between the subsystems remaining unchanged and to be reduced, such as active and reactive power (P_i, Q_i), voltage amplitude and angle (V_i, θ_i) on each individual tie line can be considered as relevant values representing system behavior of the equivalent to be established. Based on selected state variables on the tie lines, the target function defined in (2) for network reductions can be described in details where the index "org" and "eq" denote state variables in the original system and the system with the equivalent, respectively. By minimizing the target function (9) over a pre-defined integration time, parameters of individual equivalent generators and other selected controller parameters are determined at its minimum. In coping with non-linear natures of both original and equivalent models, the corresponding equivalent model can be well established with a required accuracy.

It is necessary to point out that for static network reductions, target functions can be varied from the standard form given in (9) according to different purposes of the study. For example, for setting up an equivalent used for a fundamental frequency overvoltage study, the peak value of the voltage of the system is relevant. To establish such an equivalent, the target function can be described only considering the voltage term given in (9), where the integration time can be limited to that moment where the peak voltage just passed by. In another case, if the equivalent is established for a system harmonics study, the frequency spectrum of the system is becoming relevant. Then, the target function can be described in terms of the square-errors between the frequency spectrums of the original and the equivalent model. In this case, the corresponding procedure is carried out in the frequency domain of the simulation program.

The integration of the identification algorithm provides a flexible formulation of target functions. According to different formulations of the target function, equivalents can be established to satisfy specific requirements. To achieve acceptable equivalents by using this module, however, users may need some experiences in setting up reasonable target functions. Once the target function is established, the determination of parameters of the equivalent can be automatically performed within the simulation program.

B. Automatic Procedure

A novel algorithm for dynamic network reductions has been newly developed. This algorithm performs in the time domain and uses non-linear models described in a set of differential-algebraic equations of a power system. The implementation of this algorithm into the simulation program provides an effective means for automatically establishing dynamic equivalents of a large power system. In this paper, the basic ideas of the algorithm are outlined. A detailed description and its theoretical fundamentals are discussed in a subsequent paper.

The most significant features of this module are as follows:

- Coherent generators are identified as clusters in the time domain simulation by means of the cross correlation analysis. Clusters of the coherent generators with an enhanced accuracy are determined statistically over a pre-set simulation time by analyzing characteristic similarities in waveforms of individual generators at dynamic conditions.
- To excite the power system involved a time-dependent voltage white noise is injected into the subsystem to be reduced through each tie line. Because disturbances injected have a uniform random feature, characteristics of the generator dynamic response to these disturbances can be identified independently from excitation types and fault locations.
- For establishing equivalent generators without changing established load flow condition, an "ideal" transformer with a zero-impedance and a complex rating is connected to the node where an equivalent generator is placed. By inserting "ideal" transformers, possible phase shifts of individual generator terminal voltages can be compensated.
- Controllers such as exciter and governor of individual equivalent generators are considered for the reduction. By means of the identification module described before, parameters of individual equivalent controllers are determined under transient conditions.
- Dynamic reduction runs based on non-linear models of the power system involved in the time domain simulation. In comparison with algorithms based on linearized system which are essentially only for small signal analysis, non-linear behavior of the original system, especially during critical faults (major disturbances) can be captured by the corresponding equivalent.

At first, the full power system involved is modeled with the simulation program. For establishing an equivalent, the following steps are executed to specify the subsystem to be reduced and to define the correlation index used as a criterion for the accuracy of the equivalent to be established:

- selecting the coupling nodes where the equivalent is connected, thus defining the network that is to be reduced,
- defining the tie lines between the subsystems remaining unchanged and the subsystems to be reduced where voltage white noise is injected,
- selecting the nodes which will remain in the equivalent model,
- specifying the grade of the reduction either via lowest correction index at which clusters of individual coherent generators are determined or via a number of generators that will remain in the equivalent established.

Once the above pre-selection procedure is finished, the reduction procedure runs automatically until the equivalent is established. First, the simulation program establishes a load flow condition that defines the operating point of the power system involved. After splitting the system into two subsystems, voltage white noise is injected into the subsystem to be reduced through the tie lines. The dynamic performance of the system is then simulated over a time period. Time-dependent state variables such as speed deviations of individual generators in the subsystem to be reduced are taken for the cross-correlation analysis. Coherently oscillating generators have a correlation index of 1, while generators oscillating in phase opposition share a correlation index -1. In other cases, the correlation index varies between 1 and -1. Experience shows that clusters consisting of the generators having a correlation index larger than 0.8 can provide sufficiently good results in establishing equivalent generators. Using the correlation analysis, the number of the equivalent generators is determined automatically in the procedure. Otherwise, the number of the equivalent generators can be pre-specified. All generators being identified as members of a cluster are connected to a single node via an "ideal" transformer. On this node an equivalent generator is then established. Furthermore, the passive network reduction is performed. This reduction has no influence on the short circuit and load flow behavior of the equivalent model. In addition, the algorithm can distinguish between natural generator oscillations and controller influences, realized by simulation with and without considering controllers in the procedure. As equivalent controllers, IEEE standard controllers or user-defined models can be adopted for individual equivalent generators per pre-specification, if needed. Parameters of individual equivalent controllers are determined by identification within the procedure.

The automatic procedure for dynamic network reduction can be summarized in the following steps:

- Splitting the system into two subsystems: the subsystem remaining unchanged and the subsystem to be reduced,
- Determination of the clusters of coherent generators and establishing the equivalent generators,
- Passive network reductions,
- Identifying parameters of corresponding equivalent controllers,
- Verifying the equivalent established,
- Building a new system consisting of the equivalent model established and the remained subsystem.

The implementation of the algorithm proposed into the simulation program provides a possibility to deal with dynamic reductions of large and very large power systems. Due to the fact that the simulation program NETOMAC has almost no limitation on the size of power systems, the procedure for dynamic network reductions is almost also not limited in the size of power systems.

III. CASE STUDIES

A. *Case Study I*

The power generated by hydropower stations in an Asian country will be fed into a power pool and then transmitted to the load center through HVDC transmission links. In addition to an existing HVDC link, two new ±500-kV bipole HVDC systems, each with a rated capacity of 3000 MW, will be installed.

One of the important issues is to establish AC equivalent systems for the power pool where the sending station of the HVDC link is planned. The equivalents to be established both for steady-state and dynamic modeling are mainly used for the following purposes:

- AC/DC simulation studies
- Fundamental frequency over-voltage and switching studies
- AC filter performance calculations

In Fig. 1, the 500 kV grid of the power pool is outlined. In the study, the 220 kV system was also taken into account. The rectifier station of the HVDC link is planned at "B" close to a large hydropower plant. To investigate the impact between power pool AC-system and the HVDC link, the AC equivalent shown in Fig. 1 was established nearby the rectifier station at "B".

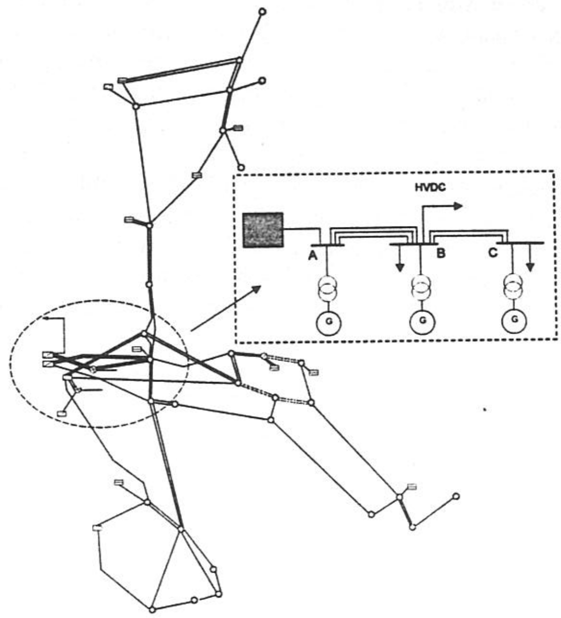


Fig. 1 Dynamic reduction of a large power system

To establish such an equivalent, the semi-automatic procedure for network reduction is applied, taking all controllers in the system and the generators involved into account. As shown in Fig. 2, starting from the same steady state condition, similar dynamic behavior of the equivalent have been achieved in comparison with the original system. Note that the short circuit capacity of the obtained equivalent (which is one of the most important characteristics for static equivalents) is also very similar to that of the original system.

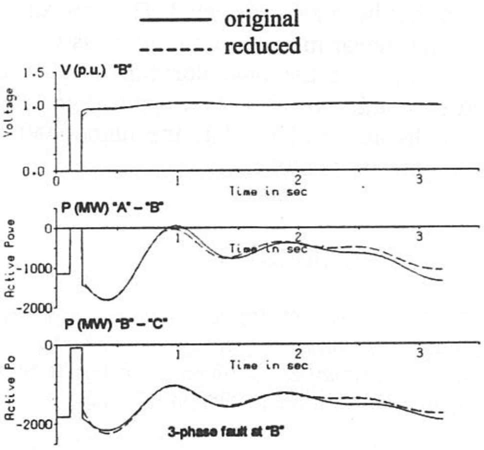


Fig. 2 Behavior of voltages, active powers

The equivalent established has been tested under different system conditions for verification of the results. The verifications have been carried out always in such a way that the system curves calculated using equivalents are compared with that calculated using the original system under the same conditions.

The verification demonstrates an adequate consistency between the original system and the reduced model. This confirms that validated again that the equivalents established with the semi-automatic procedure are valuable for practical engineering.

B. *Case Study II*

In order to test the quality of the reduction tool in practice, a data record describing the grid of UCTE/CENTREL was reduced. Calculations were executed both with the reduced and the full system model. The results are compared in the following chapters. Although a high reduction ratio was achieved, the computation results obtained with the reduced network are similar to the results of the transient stability calculations with the origin network.

The original model used as basis for building the equivalent consists of 400 generators and describes the network of the UCTE/CENTREL including the Preussen Elektra grid. In addition, a neighbouring grid is also interconnected. The different parts of the grid investigated are schematically illustrated in Fig. 3.

The original model is separated into two subsystems: one subsystem remains unchanged including the area under investigation: i. e. the northern part of Germany and the western part of Denmark. These parts are named "model of the subsystem remaining unchanged" and "neighbouring grid" hereinafter. The other subsystem of the model named "equivalent" was reduced. Both areas are interconnected via seven original interconnection lines.

Using this tool the number of generators was reduced to 49 equivalent generators. 28 generators are modelled in detail within the model of subsystem remaining unchanged and the neighbouring grid. Table 1 gives some characteristic figures about the model. Due to the fact that the common model will be used for transient stability investigations a relatively high reduction ratio was chosen.

Table 1 UCTE/CENTREL dynamic simulation model

property	Initial model	equivalent
machines	400	49+28
nodes	2000	120
branches	6700	530

For evaluating the quality of the reduced network in transient stability investigation the maximum admissible fault clearing time for three phase short circuits on the seven coupling nodes in the detailed model, connecting both the neighbouring network and the equivalent, were simulated. The node names are given in Fig. 3. These calculations have been done using the initial complete model and the interconnected equivalent model. Both results were compared. The relative deviation of the fault clearing time is given in Fig. 4 for all seven coupling nodes. The maximum deviation for the fault clearing time is –6.7%, i. e. the

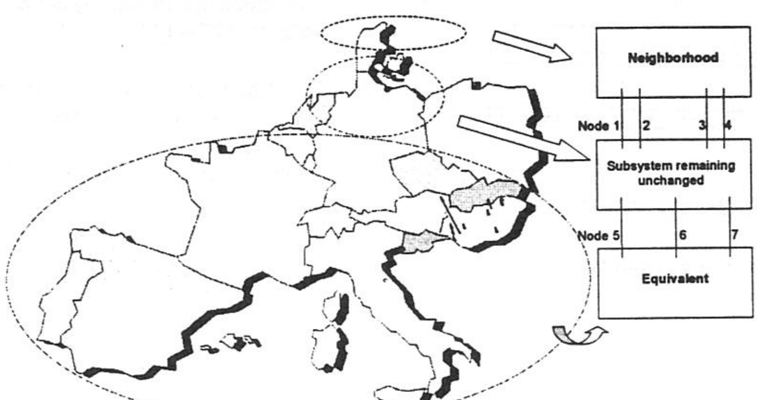


Fig. 3 Schematic illustration of the grid investigated

max. admissible fault clearing time computed using the equivalent is 6.7% lower than the fault clearing time calculated using the initial model.

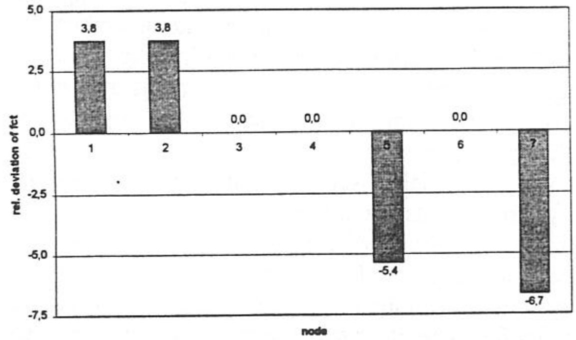
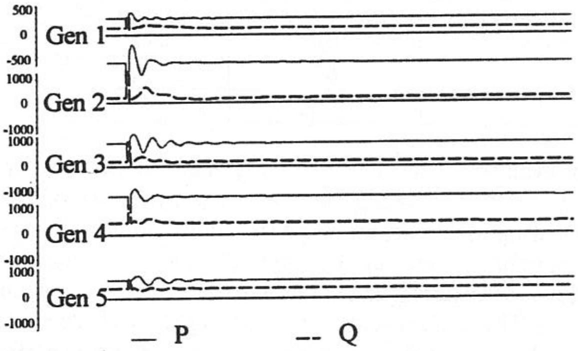
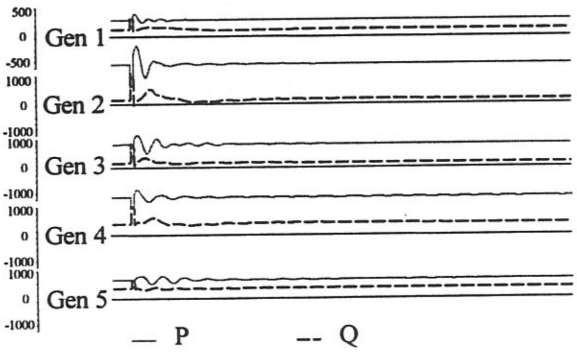


Fig. 4 Relative deviation of fault clearing time

For verification of the results a three phase short circuit at a node in the network part modelled in detail with a fault clearing time of 150 ms were calculated with both the initial complete model and the interconnected equivalent data set. The Figures below show the active and reactive power output of the generators in the detailed part of the model. The results for the initial model are given below in Fig. 5 (a) whereas the results for the total equivalent are shown in Fig. 5 (b).



a. Original network



b. Network with the equivalent

Fig. 5 Active and reactive power of generators in an event of 3-phase fault

IV. CONCLUSION

Reducing the order of large power systems became an important issue in the new deregulated market environment. A comprehensive tool for network reduction of large power systems has been presented in this paper. With the simulation program NETOMAC where two methodologies for network reduction are integrated, static and dynamic network reduction can be performed automatically or semi-automatically based on a common database. In addition to the identification module, a novel algorithm for automatic dynamic reductions has been also presented. The new algorithm is based on non-linear models using the cross correlation technique realized in the time domain. Two case studies based on two large power system applications are presented. The results achieved validate the functionality of the program for network reductions.

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