American Journal of Electrical and Electronic Engineering, 2017, Vol. 5, No. 5, 166-171
Available online at http://pubs.sciepub.com/ajeee/5/5/1

DOI:10.12691/ajeee-5-5-1

A Spatial and Temporal Evolvement OPA Simulation Method with Optimal Smart Grid Loss

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Abstract The volatility of distributed generation (DG) output power have certain effect on the planning, stability, electric quality, and the relay protection of smart grid. Therefore, traditional grid models are not suitable for the smart grid containing DG. Based on the electrical characteristics of power system, this paper takes the minimization of network loss as the optimization goal to achieve maximum benefit of smart grid. Growing-points are utilized by the OPA model established in this paper to determine the locations and the capabilities of new generation nodes, in order to offer research basis for the planning of smart grid.

Keywords: *self-organized criticality, spatial and temporal evolvement, OPA, distributed generation*

Cite This Article: Guchao Xu, Huaiyi Chen, Yixi Chen, Linru Jiang, Rong Ju, and Gang Ma, “A Spatial and Temporal Evolvement OPA Simulation Method with Optimal Smart Grid Loss.” *American Journal of Electrical and Electronic Engineering*, vol. 5, no. 5 (2017): 166-171. doi: 10.12691/ajeee-5-5-1.

1. Introduction

Nowadays, Chinese national economy is developing rapidly and people's living standard is improving. As an important national basic industry, power industry is in its high-speed development period. The extensive use of coal fuel in traditional power industry not only accelerates the fossil energy consumption, but also leads to the environment pollution and global warming issues. The trend of smart grid is to accelerate the development of clean and renewable energy and to implement the low-carbon energy power dispatch. As an important way to develop and utilize renewable energy, distributed generation (DG) can bring many benefits, such as reducing power transmission, and improving power supply reliability. However, the output power of DG is stochastic and fluctuating, so it will have a tremendous impact on the voltage and frequency of distribution network [1,2]. The large-scale access of DG will increase the aggregation degree of some special nodes, then exacerbates the unevenness of the grid structure. The change of network topology will affect the system programming, stability, protective relaying and so on [3,4,5]. Meanwhile, the access of DG aggravates the uncertainty of power flow. Large-scale power flow change and illogical topological structure will probably result in cascading failures. With the increasing penetration of distributed power, this negative impact has become more and more significant, even causes the failure of some key electrical equipment [6].

After analyzing previous blackouts, it can be found that the power grid will gradually evolve into the self-organized critical state with the accumulation of the disturbance [7]. Once the grid enters the self-organization critical state, the failure of one certain element is likely to affect the others and then expand the scope of failure. If preventive measures are not taken timely, system blackout may occur [8]. In order to comprehensively analyze the smart grid containing DG and study the mechanism of small probability event evolving into blackout, a smart grid model which fully considers DG is urgent to be established. The new model must have ability to assess the real-time state of the grid and prevent the cascading failure [9].

The researches that have done on the grid model are mostly based on the complex network theory and the complex system theory [10,11]. The complex network theory focuses on the system topology which can reflect individual interaction, while the complex system theory focuses on the self-organized criticality of systems [12]. To study deeply about the self-organized criticality of the grid containing DG, a smart grid model is built in this paper to fully reflect the features of topology and electrical parameters in smart grid. Firstly, a spatial and temporal evolvement model of smart grid containing DG is built. Then, combined with the network topology, the OPA model of smart grid is put forward. Finally, simulations are conducted to verify the correctness and validity of the model proposed in this paper, simulation results proved that the model is reliable to provide research basis for the development and planning of smart grid in different conditions.

2. Spatial and Temporal Evolvement Model Containing DG

It has been proved that the spatial and temporal evolvement model can greatly reflect the evolution rules of complex power grid in average degree, clustering coefficient, characteristic path length, and degree distribution curve [13]. The developing access capacity of DG is taken into consideration in this paper while establishing the spatial and temporal evolvement model. In order to ensure the smart grid operate reliably and achieve maximum benefit after accessing DG, the location and capacity of the new generation nodes must be determined according to the load growth and the existing network structure [14]. The access of DG will affect the existing network topology, which means transforming the traditional radial grid into the multi-power grid structure, as shown in Figure 1.

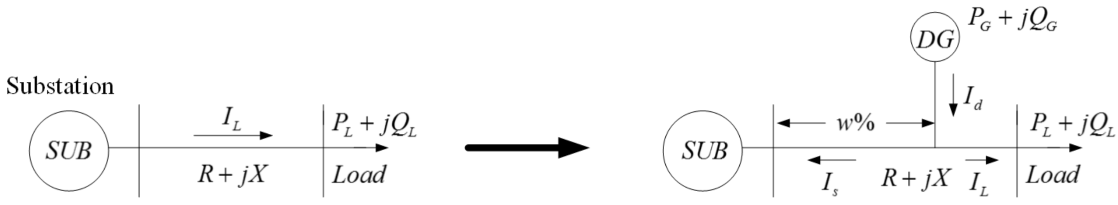

Figure 1. Diagram of grid containing DG

The total electric power loss caused by DG can be expressed as:

$$Loss = \sum_{i=1}^{N} \frac{\sum_{j=1}^{num(DG)} \left[\begin{pmatrix} P_{G_{i,j}}^2 + Q_{G_{i,j}}^2 \\ -2P_{L_i} P_{G_{i,j}} \\ -2Q_{L_i} Q_{G_{i,j}} \end{pmatrix} w_{i,j}\% \right]}{U_i^2} (R_i + jX_i) \quad (1)$$

where P_L and Q_L stand for load power, U stands for the voltage of the load terminal, P_G and Q_G stand for the output power from substation, $w\%$ stands for the proportion between the distance from DG to substation and the total length, R+jX stands for the line impedance, i stands for feeder i, j stands for the connect node of DG j.

The output power of DG is stochastic, and the geographical distribution of DG is uneven, these will pose a great challenge to the stability of the smart grid [15]. The new accessed DG usually inputs or outputs electric power by the nearby substations. There may be long distance power transmission, and in this paper it is presumed that DG needs ancillary substation in its power supply district in the early stage of smart grid construction. The growing-points are defined as the positions near the existing nodes but have not already be occupied, in order to simulate the site selection of new generation nodes in the model. To simplify the model, the capacity of DG is superimposed to the close substation so that the development of DG can be simulated by the change of substation capacity.

This paper uses nodes to represent power plants and substations while uses edges to represent transmission lines. The smart grid is abstracted as a complex network with N nodes and M edges. We use $\Sigma P_{gi}^{max} - \Sigma P_{di} \le P_M^{min}$, which means the difference between the maximum power generation and total load is less than the minimum load margin, to represent the grid is in insufficient reserve capacity situation. The model in this paper expands power supply with a probability of p_{tra} $(0 \le p_{tra} \le 1)$ and creates new power supply with a probability of $1\text{-}p_{tra}$, comprehensively considering geographical location, natural environment, line loss and so on.

A new generation node will be selected from the growing-points if needed. The linking lines between the new generation node and the others are established with a probability of P_{link}, which is jointly decided by the node degree and the distance between nodes. The physical distance l_{ij} between Node i and j can be expressed as:

$$l_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (2)$$

where x_i, x_j stand for the abscissa of Node i and j y_i, y_j stand for the ordinate of Node i and j.

The grid model is assumed to include n_0 nodes and m_0 edges initially. After t period, the new node will be connected to h_t existing nodes. h_t obeys the normal distribution as:

$$h_t \sim N(\gamma, \delta) \quad (3)$$

where γ stands for the average value of h_t, δ stands for the variance of h_t.

The amount of the edges $m_t = m_{t\text{-}1} + h_t$, the connector of node i can be expressed as:

$$\xi_i = \Big(\frac{k_i}{\sum_{j \ne i} k_j}\Big)^{\alpha} \Big(\frac{1/l_i}{\sum_{j \ne i}(1/l_j)}\Big)^{\beta} \quad (4)$$

where, k_i stands for the degree of node i and l_i stands for the physical distance between node i and the new generation node; α is a degree factor, the network topology tends to be more centralizing when α is larger; β is a physical distance factor, the network topology tends to be distributed more uniformly when β is larger. The spatial and temporal evolvement model will transfer to small-world model or scale-free model by adjusting α and β. The spatial and temporal evolvement model is proved to be with good plasticity [15,16].

The linking lines between the new generation node and the others are established with a probability of P_{link}, which can be expressed as:

$$P_{link_i} = \frac{\xi_i}{\sum_j \xi_j}. \quad (5)$$

3. Spatial and Temporal Evolvement OPA Model of Smart Grid

The AC-OPA model based on the self-organized criticality theory focuses on the influences that the change of flow makes on the self-organized criticality. The OPA model includes 2 layers of loop. The outer loop simulates line expansion and load growth to show the self-organized criticality of interconnected power grid from macroscopic view, using the ratio of load demand to transmission capacity as the characteristic quantity. The inner loop simulates AC flow to describe dynamic flow change of the grid and demonstrate the self-organized criticality of fast dynamic system from microcosmic view [17]. The spatial and temporal evolvement model established in section 2 fully reflects the statistical characteristics of the power grid. This model is a closed-loop control system combined with OPA model. The inner loop of the closed loop system simulates the dynamic power flow of the grid while the outer loop simulates the power grid construction events such as power supply expansion, load growth and lines extension.

3.1. Fast dynamic Process

Assume that the power grid operation mode in period t has been determined. The model disconnects line in a certain probability τ. If the line is overload, analyze whether the line overload is caused by DG. If the transmission line overload is caused by DG, then cut off the DG and detect the grid situation until overload disappears. Otherwise, the model starts line backup protection, then calculates load loss when the optimization successes, or disconnects power lines when the optimization fails and repeats the process until safe. The complete process is expressed as the diagram in Figure 2.

3.2 Slow Dynamic Process

First, suppose that the load growth rate of smart grid is λ. For the load nodes, the access of DG can slow down the growth rate of load. Assume the slowing speed is υ, so the periodic power grid load can be expressed as:

$$P_{di,k+1}^{\max} = (\lambda_{i,k} - v_{i,k}) P_{di,k}^{\max}$$
$$Q_{di,k+1}^{\max} = (\lambda_{i,k} - v_{i,k}) Q_{di,k}^{\max} \quad (6)$$

When $\Sigma P_{gi}^{\max} - \Sigma P_{di} \le P_M^{\min}$, the total generating capacity of the system is not enough, the spatial and temporal evolvement model will select to expand or build power supply. Suppose that the number of power supply that is allowed to be built within T cycles is N_{sub}. When the system capacity is insufficient in one cycle, determine whether new power needs to be added to the grid with a probability of N_{sub}/T. If needed, the simulation determines its access point and capacity in order to meet the minimum grid loss optimization target.

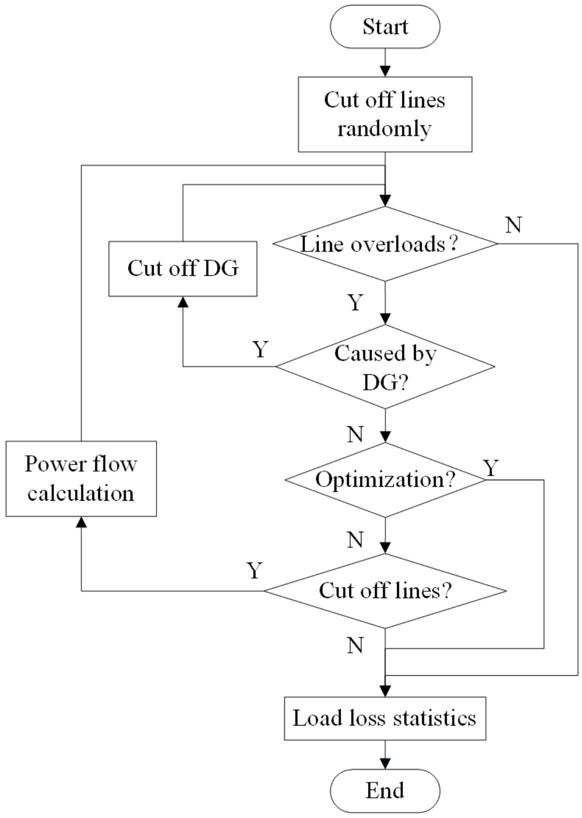

Figure 2. Diagram of fast dynamic process

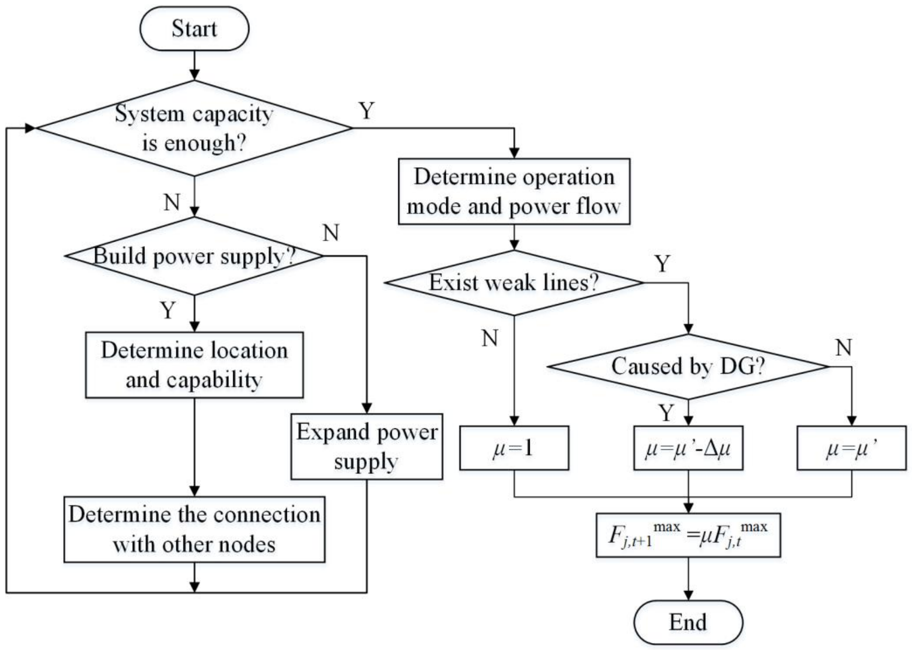

Figure 3. Diagram of slow dynamic process

Then, after the shortfall of system capacity is solved, it is also necessary to determine the power grid operation mode and whether weak line exits under the new operation mode. The given reference value ε which stands for the weak line load rate is used as the basis to judge weak lines. When $|F_{j,t}/F_{j,t}^{max}| > \varepsilon$, line j will be confirmed as the weak line, where, $F_{j,t}$ stands for the actual transmission power of line j during cycle t while $F_{j,t}^{max}$ stands for the maximum transmission power of line j during cycle t. The weak line judgment and line expansion can be summarized as:

$$F_{j,k+1}^{\max} = \mu F_{j,k}^{\max}, \quad \mu = \begin{cases} 1, & \left|\dfrac{F_{j,k}}{F_{j,k}^{\max}}\right| \le \varepsilon \\ \mu', & \left|\dfrac{F_{j,k}}{F_{j,k}^{\max}}\right| > \varepsilon \end{cases} \tag{7}$$

where, μ stands for the growth rate of line capacity, if load rate is not higher than ε, the line does not need expansion; otherwise, there are weak lines and the line capacity growth rate should be reduced if the weak line is caused by DG, $\mu=\mu'-\Delta\mu$.

Finally, the operation mode and power flow distribution are confirmed at the updated power grid state. The flow chart of the slow dynamic process is shown in Figure 3.

3.3. Complete Iterative Process

The fast dynamic process is designed to simulate the smart grid self-diagnosis in T cycles, analyze the dynamic load flow and make statistics on the relevant load loss. The slow dynamic process is designed to update the topological structure by simulating the construction and expansion of power supply (including DG) and lines. The complete iterative process is shown as Figure 4.

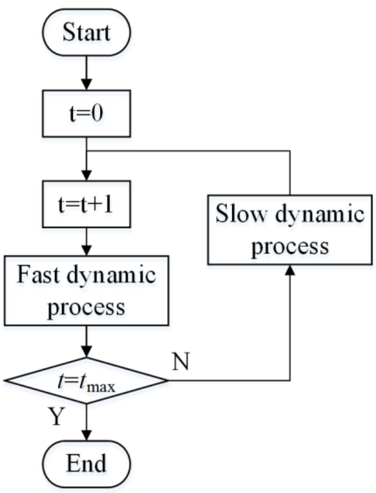

Figure 4. Complete iterative process chart

4. Simulations and Analysis

This paper simplifies the smart grid model as DG are seen to be a unit with the generator which they are connected to. The simplified grid model is shown in Figure 5, where part of the data refers to IEEE-14 node model. Based on this model, we simulate the fast and slow dynamic process of the spatial and temporal evolvement OPA model to verify its reasonableness and effectiveness.

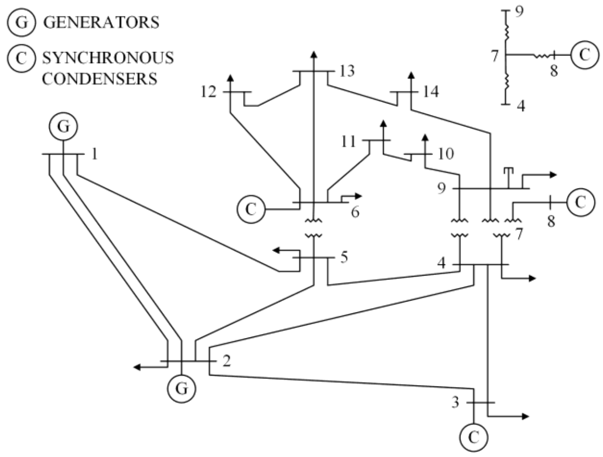

Figure 5. Diagram of the simplified grid

4.1. Parameter Settings

Assuming that the load grows at a uniform rate, according to the search, the value equals to 4.16% per year. If 3 years is a period, the load growth rate in one period is 13%. p_{tra} stands for the probability of power supply expansion, whose value in this paper is 45.2% and can be modified according to the practical demand.

The data of MATPOWER are mainly used to analyze power flow, so it does not include node coordinates. Therefore, we should add position data in the node model so as to plot diagrams. The area of growing points in this simulation is the square from (0,0) to (25,25), and α=1.5, β=4 [12].

The existing nodes and lines are shown with black dots and black lines respectively. If new nodes and lines are built, they will be shown respectively as red dots and red lines to be distinguished from old ones.

4.2. Simulation Analysis

The construction or expansion of power supply and the construction of connecting line with other nodes are probability events. Even the parameter settings are exactly the same, there will be a certain gap with simulation results. The node graph is shown in Figure 6, its total active power generation is 272.39MW while the total reactive power generation is 82.44Mvar; the active load is 259.00MW while the reactive load is 73.50Mvar.

The active load increased to 291.35MW in the first cycle. The active power cannot meet the load demand, so the model builds new power supply with the optimization target of minimum grid loss.

According to Figure 7, node 15 builds connections with five nodes, and the total line loss is 7.4378MW. The connections with node 1 and node 2 are helpful to the cooperation between power supplies, it is of great significance to the safety and reliable operation of the grid. As node 3 and node 4 are the largest load nodes, node 15 is near these two nodes and establishes connections with them, it can improve the smart grid operation efficiency. Therefore, the simulation result is reasonable.

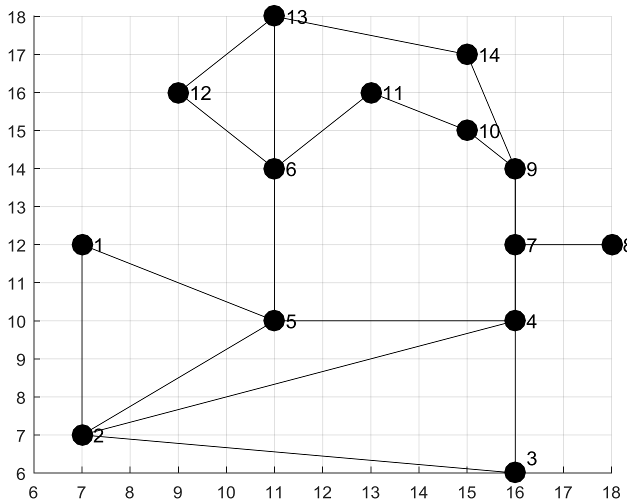

Figure 6. Schematic diagram of the node graph

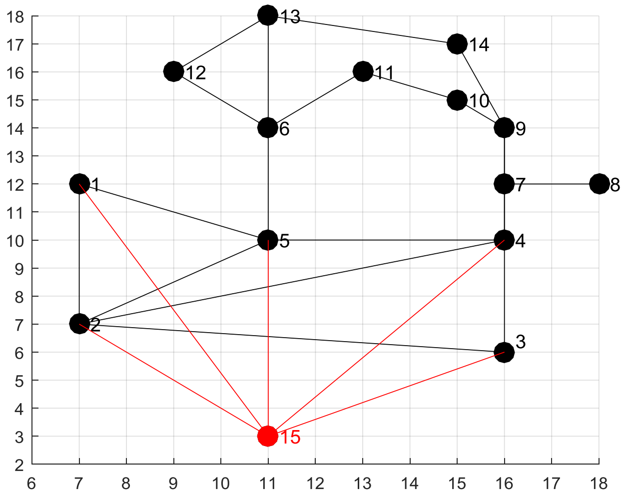

Figure 7. 15-node model schematic diagram after the first cycle

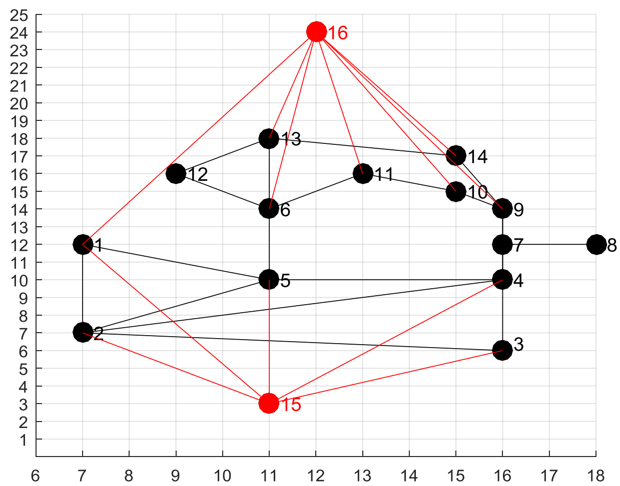

Figure 8. 16-node model schematic diagram after the second cycle

The second-cycle simulation is based on the 15-node model. Load grows to exceed the generated power and the model builds new power supply. The simulation result is shown in Figure 8.

The total line loss is 7.0717MW. The node 16, which is newly generated, is close to small load nodes and is connected to some of them.

Load growth and the active power cannot meet the load demand in the third cycle. The model expands node 1 and the expansion ratio is 150%. The total line loss is 9.0673 MW.

Run *t* cycles and the distribution trend of nodes is shown in Figure 9, new nodes tend to distribute evenly.

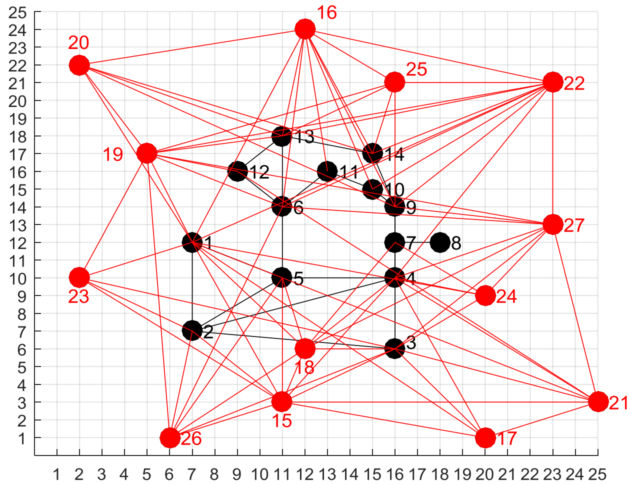

Figure 9. Schematic diagram after t cycles

5. Conclusions

In this paper, we analyze influences that DG makes on the topological structure evolution and electrical characteristics of smart grid first. Then, a more suitable model is established by combining the AC-OPA model with the spatial and temporal evolvement model. Finally, we verify the effectiveness of the model established in this paper. The simulation results show that the construction and expansion in this model meet the basic requirements of the reliability and economy of smart grid. This model can provide reliable model basis for self-organized criticality researches and the smart grid planning researches. However, some influence factors still remain to be further studied, such as the role change of DG and the faults agglomeration caused by the rise of failure probability under bad weather conditions.

Acknowledgements

This research was supported by Postgraduate Research & Practice Innovation Program of Jiangsu Province (SJCX17_0340).

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