A SIMULATION TOOL TO STUDY WIDE-AREA CONTROL SYSTEMS

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Abstract - Power system dynamic simulation programs serve as valuable design and analysis tools to study the response of the system to various system conditions and events. Due to the increasing use of wide-area measurement & control (WAM & C) systems, need for a dynamic simulation tool with additional capabilities to simulate protective relays, wide-area measurement & control and the associated communication network is felt. One such prototype program has been developed which includes these features in the dynamic simulation program. This novel simulation tool facilitates easy simulation of various communication and wide-area control schemes. It can be used to determine the performance of wide-area control schemes for real-time control, and the feasibility of a communication network for such schemes can also be observed. Unlike local relays, wide-area measurement & control schemes involve data communication from various substations to the control center. Such data communication networks were simulated using user-supplied values of measurement delay, signal propagation delay and data concentrator throughput to determine the net delay associated with the communication of a measurement or control signal. Results demonstrating the capabilities of this dynamic simulation tool are presented.

Keywords - Power System Stability, Power System Dynamics, Dynamic Simulation, Relays, Wide-Area Measurement & Control, Special Protection Schemes, Communication.

1 INTRODUCTION

DURING the last decades, power systems around the world have suffered a number of severe disturbances, breakdowns and voltage collapses [1–4, 6, 7]. These problems are mostly related to high stress levels in the networks. The character and effect of these stresses, is usually system-wide. Therefore protection systems, using data from more locations as well as acting with a wide-area scope, have been proposed, designed and in some cases installed to handle them. These are most often referred to as Special Protection Schemes (SPS) [8–10]. Typical features of such schemes include wide-area measurements, communications, central control computers, etc [11]. Communication systems are crucial in a wide-area measurement & control system [12]. Latency associated with the communication system have significant effects on the system control and dynamics. Thus, dynamic simulation tools require capabilities to model and simulate protective relays, WAM & C and data communication systems.

The existing power system analysis tools are limited in their ability to incorporate wide-area communications and controls into their simulation algorithms. Some simulation programs provide limited user-programming capability to model specific schemes. But every time the scheme changes or a new SPS is installed, a new user-program has to be written. An integrated dynamic simulation program, having the capabilities to simulate local relay protection schemes, wide-area measurement & control schemes and communications, is required. Availability of such modeling capability that requires data input rather than new programming, facilitates testing of various control and communication schemes.

Such a power system dynamic simulation program, with additional capabilities to simulate the protection, communication and wide-area measurement & control systems, was developed as a prototype. Using this tool, effects of protection system actions and communication delays on system dynamics can all be studied together. Applicability of Special Protection Schemes (SPS), designed for specific system conditions can be tested. Events leading to cascading blackouts, interarea oscillations, etc can be simulated and control actions to avoid a system instability/failure can be determined through off-line studies. Study of the effects of communication network on system dynamics helps in determining the requirements on the communication system, for fast and reliable operations.

2 SYSTEM COMPONENT MODELS

Dynamic simulation of power systems requires models to represent the various components of the system. For this prototype one standard two-axis (fourth order) model was used to represent the synchronous machines. For Exciter, Power System Stabilizer (PSS) and Governor representation, standard models available in present-day simulation programs were used. The ZIP load model, described in [13], was used to represent loads. The following relay models were included: Overfrequency Relay, Underfrequency Load Shedding Relay, Inverse-time Line Overcurrent Relay and Distance Relays (Zone I and Zone II).

Communication systems play a significant role in power system protection schemes involving wide-area measurement & control system. These systems distribute and manage the information, which is then used for analysis and control/protection of the system. To meet the reliability and security requirements, the communication network needs to be designed for fast, robust and reliable operation. The most important factors that influence the realization of these objectives are: the type, the topology, the protocol and the medium used for the communication network [13]. The speed of the communication system is a function of the communication protocol and the media bandwidth, the frequency and volume of information communicated and the handling of communication errors. In this program, the values of the various delays associated with the components of the communication network is supplied as an input by the user. The program calculates the net signal delay from the substation to the control center or vice-versa. The effect of communication delay is modeled by delaying the control action in the program by the net delay times.

3 INCORPORATING SPS IN THE DYNAMIC SIMULATION

A flow chart of the dynamic simulation approach is given in Fig. 1. The starting point for any power system dynamic simulation program is the predisturbance power flow solution (**Step 2**). The disturbance is simulated by changing the bus admittance matrix, shown in **Step 3** of the flow chart. The change in system variables due to this disturbance is tracked by numerically integrating the coupled set of differential and algebraic equations (**Step 6 & 7**).

The heart of the program is the main simulation loop shown as ‘Dynamic Simulation Loop’ in the flow chart in Fig. 1. Here, the solution of the differential and algebraic equations are obtained at each time-step and the state variables are updated. MATLAB was used to develop this prototype program and this loop is implemented in the program by calling the MATLAB function *ode45* [14] with a start time, an end time, and the initial values of the state variables for this interval. a production grade program, obviously, would not use MATLAB as run times would be important.

To implement relay checking routine, another feature of the *ode45* function called *OutputFcn* was used at the end of each time-step (**Step 8**). The system variables are checked for their limits and if any breaker/recloser or special control action is required, the output status of this function changes to ‘1’ and the program exits the integration loop (**Step 11**). For breaker/recloser action, which are local actions, timers are set according to the relay settings. But for a control action due to the Special Protection Scheme, which involves wide-area communications, the net delay for the control action has to be calculated (**Step 12**). These calculations have to take into account the delays due to communications as explained in the next section. The pending action for the current time, if any. is then performed (**Step 13**) and the time interval for the next call to the *ode45* routine is updated (**Step 14**). The start time is set as the time when the previous *ode45* call exited. The end time is the most urgent of all pending breaker/recloser action time. The final values of the state variables from the last call to the function are used as the initial values for the next call.

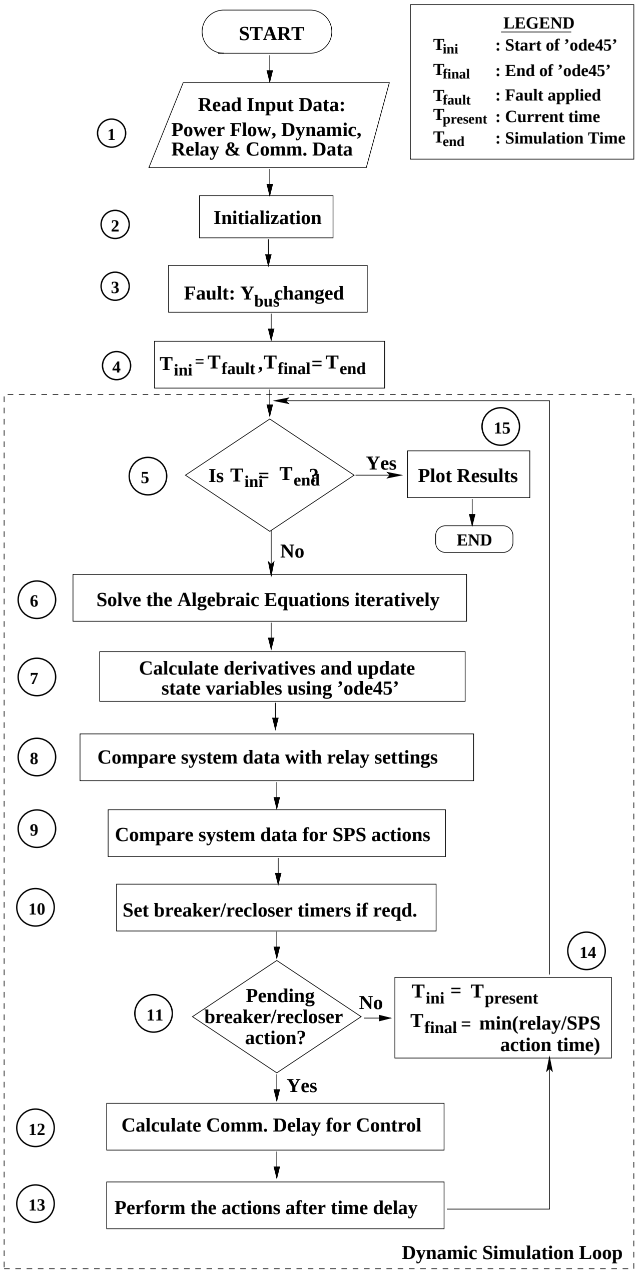

Figure 1: Flow Chart of the Dynamic Simulation Program

Simulation of the Special Protection Scheme is also done using the *OutputFcn* feature of *ode45*. Similar to the implementation of relays, the SPS logic is applied on the system variables to determine any required control action (**Step 9**). This is done at each time-step. The program can be modified to do this operation every t secs. (user-specified), instead of every time-step. In an actual system, the SPS logic unit is located at the control center. Thus, SPS involves communication of measurement data from the substations to the control center and that of control signals from the control center to the devices at the substations. Thus, the time for control action due to the SPS has to take the communication delays into account.

4 MODELING THE COMMUNICATION TOPOLOGY

Data communication involves various types of delays. Although for fiber-optic communication channels the propagation delay is almost negligible, the delays due to queuing and processing can be significant and may have a pronounced impact on system stability. To determine wide-area control actions, measurement data from various locations in the network is required. Communication of data from different locations experience different amount of delays before they reach the control center. For SPS, these data from various locations need to be synchronized in time. Schemes like GPS time-stamping of data, etc are used in practice.

For this work two different communication topologies, denoted here as *mesh* and *star*, were simulated. For both of these topologies the system is divided into three areas with no inter-area communication links. Each of these areas has a data concentrator, which can be located at some prespecified node (substation) in the area. Data is routed from the substations to the data concentrator through the communication links. The data concentrator synchronizes and time stamps the data before passing it to the control center above it. The control center processes this data to decide if some control actions are required and generates those control signals. The control signal/s from the control center is likewise routed down to the substations where the control device is located.

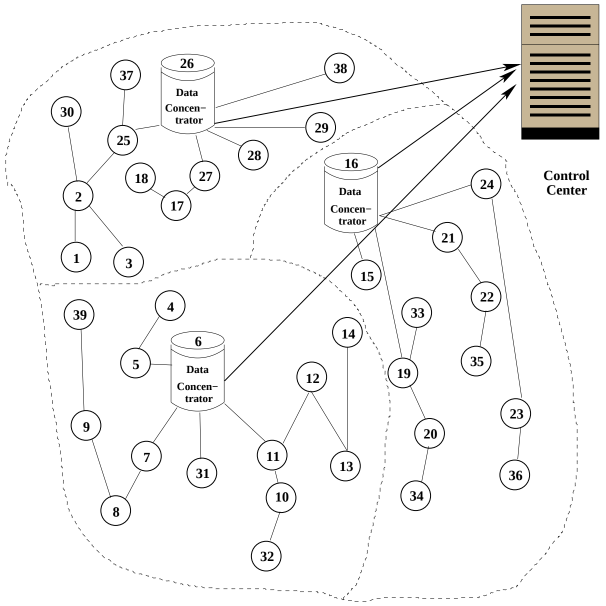

Figure 2: Mesh Topology for Communication Network: Only minimum-hop routes to data concentrator shown in figure

The mesh topology assumes the communication network similar to the power transmission network with communication nodes at the substations and communication links along the power lines. To generate the test case presented here, the communication paths are assumed to be minimum-hop paths from the substation to the control center. These paths are shown in the schematic diagram of this topology in Fig. 2. However other links leading to alternate redundant paths exist but are not shown in the diagram, for clarity.

The star topology, shown in Fig. 3, assumes that every substation in an area has a direct communication link to the data concentrator in its area. This data concentrator can be at a substation or it can be a special node. Measurement data is directly transmitted to the data concentrator which then passes it on to the control center after synchronization and time-stamping. This topology undoubtedly leads to faster data communication but it is costly since it involves dedicated links to each substation. The right of way available from the power transmission system may not be adequate for this communication network topology and additional right of way might be needed for the communication links.

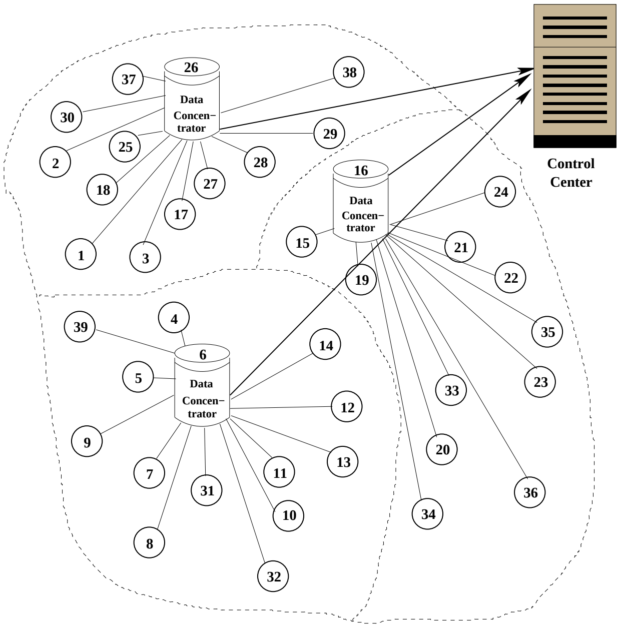

Figure 3: Star topology for Communication Network: Each substation is directly connected to the data concentrator

Signal latency is calculated by adding fixed measurement delay, concentrator throughput and transfer trip latency and processing time to the variable latency time determined from the number of hops required for the data to reach from the substation to the control center and finally to the control device location. A hop is taken as a link from one substation to another. Other complex delay logic/algorithm can be implemented.

Typical delay times associated with such a system are given in Table 1. The total delay time assuming a single hop is around 10 cycles for tripping and 13 cycles for closing (167 and 217 ms). Intentional time delay and throughput delay will be 67 ms or longer. These typical timings were obtained from industry and used as input data for our communication model.

Event	Delay(60 Hz cycles)
Phasor Measurement	3
Fiber Optic Communication	2
Data Concentrator Throughput	2
Transfer Trip	1
Circuit Breaker Tripping	2
Circuit Breaker Reclosing	5

Table 1: Typical Delay Times

5 SIMULATION RESULTS

A single-line diagram of the IEEE 39 bus test system is shown in Fig. 4, for reference. To generate cases of instability, the transmission system was stressed by increasing the loads and the generations in the system and applying a balanced three phase fault on a transmission line. Wide-area controls including special protection schemes for these cases were determined to generate control signals to prevent the system from going unstable.

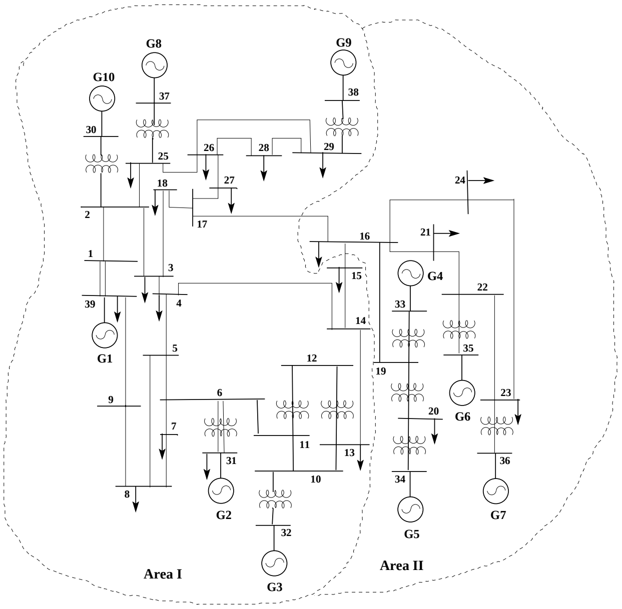

Figure 4: Single-line diagram of the IEEE 39-Bus Test System

In the test system, if generators 4, 5, 6 and 7 (on the right hand side of Fig. 4) sell significant power to the buses on the left hand side, all of the transfer of power flows through bus 16 on two transmission lines, 16-17 and 16-15. Such a base case with high flows was generated by increasing the generation by 25% on these generators to supply a similarly increased load on buses on the upper right. A balanced, three-phase, permanent fault (with no reclosure) on line 16-17 was then studied. Fig. 5 shows that this fault results in first swing instability. In fact, it can be seen in Fig. 5 that the generators 4-7 swing together and this group distinctly separates from the rest of the generators.

This scenario obviously leads to cascading failures depending on the settings of local protection. Second and third zones of distance relays, under-frequency load shedding and over-frequency generator tripping could all play a role in the final state of the system, which is bound to be quite diminished if not a complete blackout. The limit on the total transfer on lines 16-17 and 16-15 must be set significantly lower than the base case studied here resulting in less economic generation. However, since these two lines form a transmission bottleneck one could consider a special protection scheme that will open the other transmission line when either one sees a fault, thus separating the system into two areas, shown in Fig. 4 as Area I and Area II. Such a separation could save most of the system.

5.1 *Designing the SPS*

It is assumed that time-stamped bus angles are being measured together with other system variables at all substations and are being transmitted through a communication network to the SPS logic in the control center. The SPS can then send control signals over the same network back to all the substations.

The following logic was used:

1. If the angle separation between the generator groups exceeds a pre-specified value (70 ° was used in the following cases), Area I and Area II will be separated. In this particular case, the faulted line 16-17 will open because of its distance relay and so the SPS will have to open line 16-15 to separate.
2. The load and generation in Area I are balanced by shedding load at various buses.
3. The load and generation in Area II are balanced by tripping generator 6 and switching on a dynamic brake at bus 20.

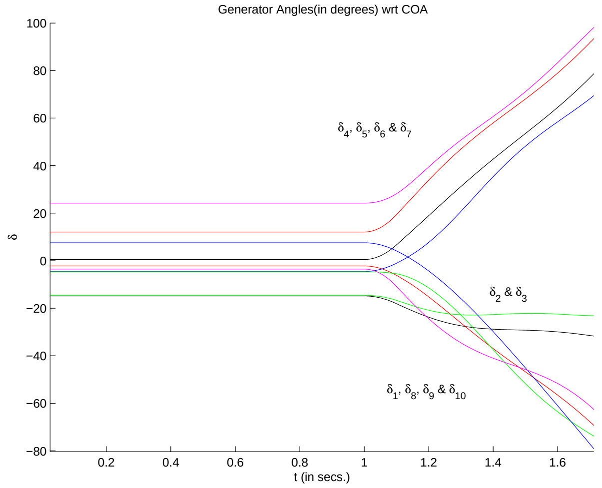

Figure 5: Without any SPS control action the system separates following a fault

5.2 *Effects of the communication topology*

The effects of various communication topologies and communication errors were studied using the above SPS design on this case. Typical communication times mentioned in Section 4 were used. If the mesh topology is used, the maximum control signal delay was 233 ms., and the areas did not stabilize. The angle plot for such a case looks similar to Fig. 5. If the star topology is used, the net delay for each control signal was less than 153 ms., and both areas stabilized after some oscillations. The generator angles for Area I and Area II for this stable case is shown in Figs. 6 and 7 respectively. This demonstrates that the communication topology is extremely important and is a major limitation of possible controls.

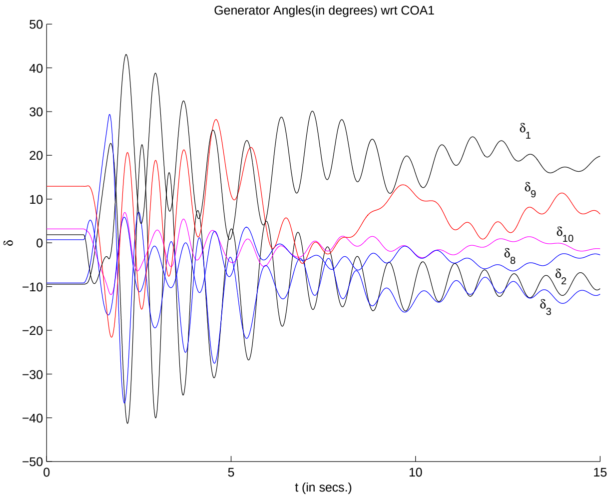

Figure 6: Angles of generators in Area I with SPS control action using the star topology. All SPS control signal delays are 153ms or less

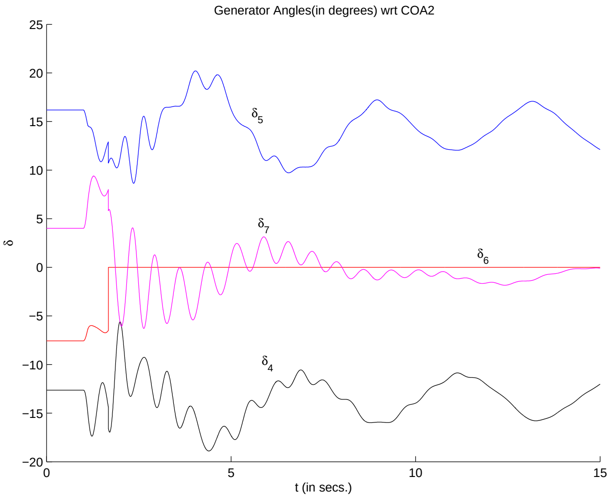

Figure 7: Angles of generators in Area II with SPS control action using the star topology. All SPS control signal delays are 153ms or less

Effects of communication errors can also be studied using this simulation tool. Let us take the same case using the same SPS logic and the star communication topology, but let us assume a communication failure to the dynamic brake at bus 20. The generator angles for Areas I and II are shown in Figs. 8 and 9 respectively. As can be expected, without the dynamic brake balancing the power, the generators in Area II trip on over-frequency while Area I stabilizes as before.

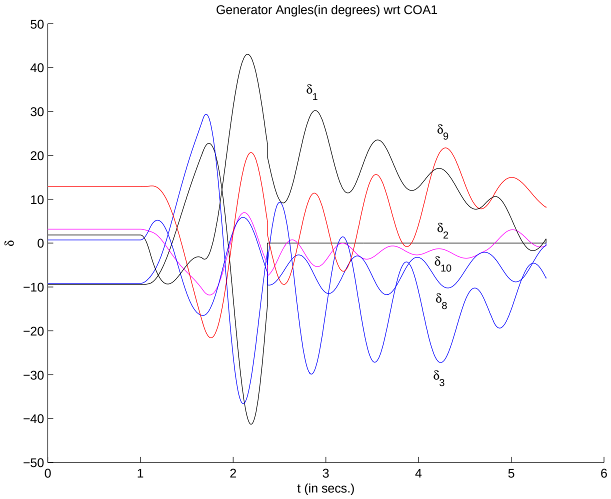

Figure 8: Angles of generators in Area I with SPS using star topology: Failure of communication signal to switch in the resistive brake on bus 20.

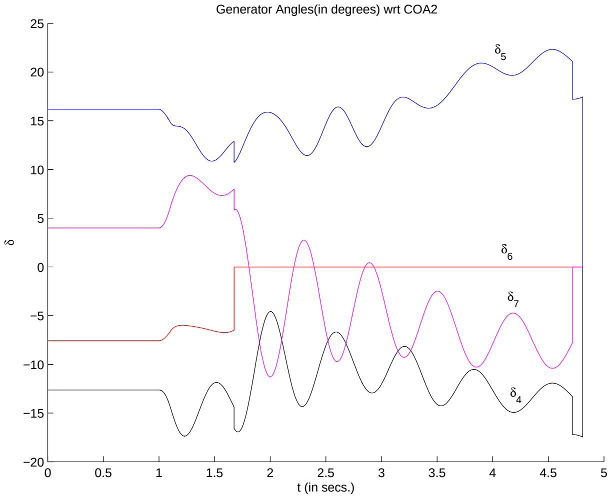

Figure 9: Angles of generators in Area II with SPS using star topology: Failure of communication signal to switch in the resistive brake on bus 20.

6 CONCLUSION

Thus we have seen that this program can be very effectively used to simulate the effects of communications and wide-area measurement & control systems on the dynamic response of a power system. This modeling capability can form a basis for developing commercial-grade dynamic simulation software that can be used to design and test the more sophisticated controls developed today. The simulation program needs SPS and communication models that can be defined by input data.

The test results also validate that communication topology and latency have a significant effect on the dynamic response of a power system. This is specially true in emergency situations where the communication networks are used to relay critical control signals to the devices. However communication delays are equally important in the relaying of measurement data to the control center. As seen in the scenario for transient instability, the mesh topology was unable to stabilize the system since the delays to send the measurement data from the substations to the control center were quite high. Of course, time available for controlling such a case of transient instability is very short and even small delays in communication are critical. These delays may be less significant for the cases of oscillatory instability as the time to instability, and hence for control, is higher. Communication systems can be designed so that control signals to avoid transient instability, can be given higher priority for communication through the network. This simulation tool can be very effectively used to do similar studies to design wide-area control schemes and data communication networks for real-time control.

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