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Power System Transient Stability Enhancement with TCSC Controller Using Genetic Algorithm Optimization

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Abstract

In this paper, a method is presented for modeling and parameters setting of thyristor controlled series capacitor (TCSC) controller in multi-machine power system to improve transient stability. In this paper will explain the computational effectiveness and efficiency of the genetic algorithm (GA) optimization techniques for setting TCSC-based controller parameters in front of non-linear optimization problem and in a simulation environment is run. With a minimum objective function, which will include the generators rotor angle oscillation changes, will improve the system transient stability. The proposed TCSC controller on a multi-machine system is tested and simulation results for performance accuracy are presented. The non-linear simulation results confirm the impact of the proposed method to improve transient stability of power system in a multi-machine with a TCSC controller. The simulation results also show that the proposed TCSC controller to be effective in damping of low-frequency oscillations.

Keywords: FACTS; TCSC; Genetic algorithm; Transient stability; Digsilent environment

INTRODUCTION

In recent years, by rapid development of semi-conductor industries and control systems compensator using high speed controllable electronics devices becomes more popular [1,2]. These devices are called flexible ac transmission systems (FACTS) [3,4]. TCSC is one of the most FACTS family members that widely in long transmission lines in power systems are used [5,6]. This compensator can take on different roles in the operation and control of power systems including power transmission planning, reducing asymmetric components, reducing network losses, creating reliable voltage, short circuit current limitation, reducing sub-synchronous resonance, damping power oscillation and accessing transient stability of the system [7,8].

GA technique is finding popularity within research community as design tools and problem solvers because of its flexibility and ability to achieve optimal parameters of control system closer to the overall minimum that is complex and difficult to solve by conventional optimization methods [9,10]. Unlike the other techniques, GA does not need to continuous or discrete variable optimization problems. It only needs to be calculated solved problems. GA has been built based on search processes on the mechanisms of natural selection and survival of generations [11,12]. GAs uses multiple points of search instead of a search point. And they work with the coded structure of variables instead of real variables. In this method only requires the objective function for search, to find an overall simple optimal [13,14].

Advantages of GA are obvious. GA is a very powerful optimization tool, which can provide global optimal solution to any type of optimization problem. For example, its application can be found in [15,16] for optimization problems. Therefore, GA offers an improved access, to accommodate irregular search space of an optimization problem.

A graphical user interface based on a GA to find the optimal locations and sizing parameters of multi-type FACTS devices in large power systems is to maximize the system static loadability presented in [17]. A multi-objective GA approach base on Pareto method type to tune the parameters of a TCSC for power system stability improvement is presented in [18], which by minimizing the time-domain based multi objective function stability performance of the system is improved. A lead-lag structure as a main damping controller for a static SVC to diminish power system oscillations is proposed in [19], which the GA optimization technique was applied to solve an optimization problem and to achieve optimal parameters of the SVC-based supplementary damping controllers and PSS. A combination of TCSC and PSS in order to enhance the stability of multi-machine system presents in [20], which the parameters of these controllers are optimized by velocity update relaxation particle swarm optimization (VURPSO) algorithm and GA.

In the presented paper, GA is used for simulation of TCSC controller parameters setting. Recent advances in the telecom industry with efficiency increase in technologies, such as phase measurement unit (PMU) that is involved, offer a reliable source of wide area amounts power system dynamic state. Many papers research on the proper use of this information in various areas of power system dynamic performance. Although local control signals are easy to obtain but they are not controllable and observable for wide area signals in oscillating modes of internal region. Due to restrictions on local measurements, the controllers based on local signal cases problems in the proper performance of the system different operating conditions. With rapid advances in wide area monitoring system (WAMS) technology, fast communication networks and powerful information technology, spread and distinct signals in power systems, can be focused and events are processed in real time. This, for wide area signals provides a good choice for input of control system. TCSC reactance setting is a complex dynamic process. Result of careful design and evaluation of control strategies depends on the accuracy of the simulation is in this stage [21,22].

In this paper a simple model of transfer function related to TCSC controller based on velocity oscillation are presented as input. This model is presented in Digsilent environment. GA based on optimal regulation algorithm is used to setting of TCSC controller. TCSC controller efficiency is evaluated on nine buses three machines power system. To improve system transient stability, location of controller is selected in the hardest position so that it is minimum. In this paper is provided a dynamic modeling of TCSC in S part, and is studied multi-machine power system in third part. Then location of TCSC is determined under the hardest error conditions. In fourth part the TCSC controller transfer function is presented and is formulated optimization problem. In fifth part application of GA is evaluated in optimization problem. In sixth part result of simulation is presented.

Thyristor Controlled Series Capacitor

Variable impedance devices using power electronic technology have the potential to increase power control and system damping. TCSC is one of the most important and best known series FACTS controllers. The basic structure and model of the TCSC is shown in Fig. 1 [23].

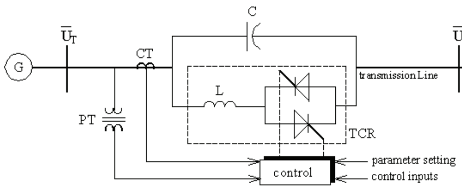

Figure 1. Single-machine infinite-bus power system with TCSC

It consists of a fixed series capacitor (FC) in parallel with a thyristor controlled reactor (TCR). A parameter to describe the TCSC main circuit is the compensation ratio (λ), which is the quotient of the resonant frequency and the network frequency [24]:

$$\lambda = \sqrt{\frac{X_C}{X_L}} = \frac{1}{\omega}\sqrt{\frac{1}{LC}} \tag{1}$$

where XC is the nominal reactance of the fixed capacitor C at the fundamental frequency. Reasonable values for λ fall in the range of 2 to 4. Assuming that the total current passing through the TCSC is sinusoidal; the equivalent reactance at the fundamental frequency can be represented as a variable reactance XT [25,26]:

$$X_T = X_C[1 - \frac{\lambda^2}{\lambda^2 - 1}\frac{\sigma + s}{\pi} + \frac{4\lambda^2 \cos^2(\sigma/2)}{\pi(\lambda^2 - 1)^2}(\lambda \tan\frac{\lambda\sigma}{2} - \tan\frac{\sigma}{2}] \tag{2}$$

The input-output relationships can be seen in Fig. 2 by drawing the three dimensional plot of the control surface versus the two inputs. It can be observed that, for a given λ, the value of equivalent reactance (XT) can be controlled by adjusting α.

So $X_{TCSCmin} \leq X_{TCSC} \leq X_{TCSCmax}$.

With $X_{TCSCmax} = X_{TCSC}(\alpha_{min})$ and $X_{TCSCmin} = X_{TCSC}(180^o)$.

In this paper, the controller for performance has been considered only in the capacitive region. It means $\alpha_{min} > \alpha_r$ that αr is related to the resonance point. The inductance area associated with $90 < \alpha < \alpha_r$ provides high harmonics that in stability studies cannot be modeled.

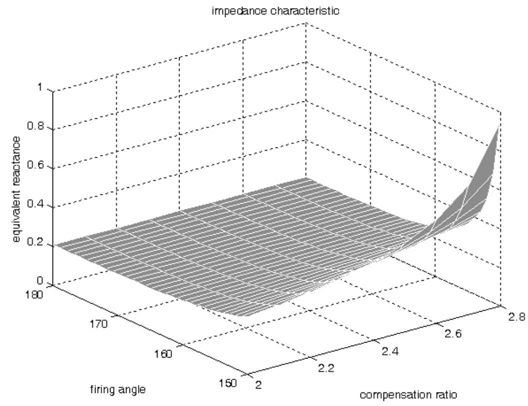

Figure 2. Effect of firing angle and compensation ratio on equivalent reactance

Power System under Study

In Fig. 3 the popular western system coordinated council (WSCC) nine buses three machines practical power system is shown. It is observed, the generators are shown by a flux-decay appropriate model, regardless of the transient and saturated reactance for simulation. So regardless of the turbine governor dynamics, Tmi (mechanical torque input) remains constant. The dynamic of the generator can be expressed by the following differential equations [27,28]:

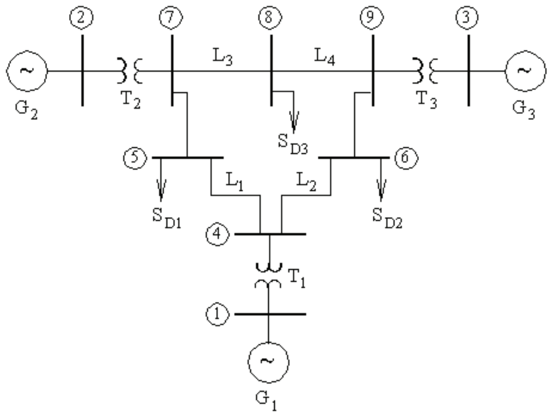

Figure 3. Power system under study

$$\frac{d}{dt}\delta = 2\pi f_o \delta \tag{3}$$

$$\frac{d}{dt}\omega = \frac{1}{2H}(P_M - P_E - K_D\,\omega) \tag{4}$$

$$\frac{d}{dt}E'_q = \frac{1}{T'_d}[E_F - E'_q + (X'_d - X_d)i_d] \tag{5}$$

where δ is angle load, f_o is operating frequency, H is the generator inertia constant, KD is the inherent damping constant, ω is angular velocity, PM is mechanical power input, E'_q is voltage proportional to direct axis flux linkages, X'_d is direct axis transient reactance, id is direct axis components of armature current, T'_{do} is the d-axis open circuit transient time constant and X_d is direct axis components reactance [29].

In this model, the loads are considered as constant impedance and according to relationship (6) are converted to admittance:

$$\overline{Y}_{Li} = \frac{P_L - jQ_L}{V_i^2} \qquad i = 1, \ldots, m \qquad (6)$$

The system was modeled by using the above equations in the Digsilent environment. Power system stabilizers are installed for 2 and 3 machines. For simplification, speed governor dynamics are not modeled and power system stabilizers are modeled by using Digsilent blocks. Power oscillations associated with synchronous mach-ines are inputs of these stabilizers. Also, a simplified exciter consists of efficiency and a time constant is used for all machines. By changing the network parameters, due to certain events of line, variable values are changed in the above equations. The first step in controller design based on Facts, in a multi-machine power system, is selection of the best location. In this paper, to find the location TCSC controller, a three-phase fault near to bus and at the end of a line is applied and this error disappears with the removal of the line. This process is repeated for all possible conditions, to finding the most difficult position that is called critical clearing time (CCT) error. To calculate of CCT, the machine equations are expressed as state variable form. Voltage of transient reactance model is used for generators and phase angle difference in each machine associated with the main bus [30]. The result of CCT values are presented in Table II. The results presented in Table I shows that the hardest position (called minimum CCT) occurs in 0.16 S that a three phase fault applied at bus 7 and it eliminates with removal of line from bus 5 to bus 7.

Table 1. Data the power system

Component	**Value**
G1	16.5 kV, X=1.04pu, Slack Bus
G2	18.0kV, 163MW, X=1.025pu
G3	13.8kV, 85MW, X=1.025pu
T1	16.5/230, X=0.0578
T2	18/230, X=0.0625
T3	13.8/230, X=0.0568
L1	R=0.032, X=0.161, Y=0.163
L2	R=0.039, X=0.17, Y=0.179
L3	R=0.0085, X=0.072, Y=0.0745
L4	R=0.0119, X=0.1008, Y=0.1045
SD1	125MW, 50MVar
SD2	90MW, 30MVar
Generator	H_1=23.64, H_2=6.4, H_3=3.01, K_{D1}=0.1, K_{D2}=0.2, K_{D3}=0.3, X_{d1}=0.146, X_{d2}=0.8958, X_{d3}=1.3125, X'_{d1}=0.0608, X'_{d2}=0.1198, X'_{d3}=0.1813, X'_{q1}=0.969, X'_{q2}=0.8645, X'_{q3}=1.2578 T'_{do1}=8.96, T'_{do2}=6.0, T'_{do3}=5.89
Exciter	K_A=20, T_A=0.2
TCSC Controller	T_{TCSC}=15, X_C=0.02376, K=2, T_1=T_3, T_2=T_4, T_{WS}=10 $X_{TCSCMAX}$=0.576 (80% of line), $X_{TCSCMIN}$=0
PSS	T_S=0.03, K=20, T_W=2, T_{1S}=0.05, T_{2S}=0.02, T_{3S}=3.0, T_{4S}=5.4, V_{SMAX}=0.15, V_{SMIN}=-0.15

Table 2. CCT Values for the error in different points

Bus No.	**From bus**	**To bus**	**CCT in second**
4	4	5	0.3
4	4	6	0.3
5	5	4	0.35
5	5	7	0.31
6	6	4	0.44
6	6	9	0.38
7	7	5	0.16
7	7	8	0.18
8	8	7	0.25
8	8	9	0.3
9	9	6	0.21
9	9	8	0.23

Problem Formulation

In this paper, lag-lead structure has been chosen as the TCSC controller. TCSC controller structure is shown in Fig. 4 that it includes a gain block with K_p coefficient, a Washout signal block and two-stage fuzzy compensa-tor Block. As shown in Figure, block of fuzzy compensa-tor provides suitable lead properties for lag compensation between input and output signals. The washout signal block is used as a high pass filter with T_W as time constant. Where the signals associated with oscillations in the input signal, will be allowed to pass without any change. While without it, a permanent change in input causes a change in system output. Form Point of view washout function, the value of T_W is not critical and may be in the range 1 to 20 sec [31]. In Fig. 3, s_o is the angle of initial conduction, which is determ-inant for power flow control loop. Power flow control loop, in practice works completely slowly and therefore assumes that s_o remains constant during the period of high turbulence. TCSC controller transfer function is as follows:

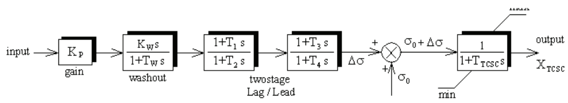

Figure 4. Structure of TCSC controller

$$u = k_p\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)y \qquad (7)$$

y and u are the input and output signals respectively in the TCSC controller. In this structure TW is usually predetermined and is considered about 10 s.

Thus in both lag and lead compensator, T_1=T_3 and T_2=T_4 are assumed. K_P is controller coefficient and T_1 and T_2 are time constant, which are determined. In this paper, the proposed TCSC controller signal is error of speed differences (w_1-w_2) and output varies in conduction angle Ds. Initially, error of speed for No. 2 machine, respect to slack bus becomes per unit. And this signal is passed through an integral. And it is used as input in the TCSC controller. In steady state: $X_{EFE}=X_T+X_L-X_{TCSC}(a_o)$ and Ds=0. In this situation, Series compensation dynamic conditions will be moderated for damping of system oscillations. The effective reactance in dynamic situations is equal to $X_{EFE}=X_T+X_L$-

X_{TCSC}(a), that s=so+Ds, s=2(p-a), and a_o and s_o are initial fire angle and initial conduction angle respectively. Objective function is expressed as the following equation:

$$J = \sum \int_0^{t_1} \left[\Delta\omega_2(t,x) - \Delta\omega_1(t,x)\right]^2 dt \quad (8)$$

That Dw_{12}(t,x), Dw_2(t,x) are error of rotor speed related to 1and 2 machines for setting of X parameters of controller. (Note: X parameters are TCSC controller parameters, including the K_p and $T_1$and T_2) and t1 is a period of time for simulation. For calculation of objective function, simulation in one period and in time domain is executed for power system model. To minimization of this objective function for improvement of system response the sitting and rising times are evaluated. Limitations of problem are parameters ranges in the TCSC controller. Therefore, design problems can be formulated as the following optimization problem.

Minimize J (9)

with following conditions:

$$K_p^{min} \le K_p \le K_p^{max}$$
$$T_1^{min} \le T_1 \le T_1^{max} \quad (10)$$
$$T_2^{min} \le T_2 \le T_2^{max}$$

The proposed GA approach is used for solving the optimization problem and consideration to parameters optimal setting for the TCSC controller.

Algorithm Genetic

In this paper, GA is used to optimal setting of controller parameters x in TCSC compensator, and to min-imization of objective function J. When GA is applied a number of parameters need to initial value. An appropriate choice of these parameters is effective on the convergence speed of algorithm. Table III shows the initial value of parameters in the GA. Normalized geometric classification, which is one of the classification met-hods, as a function for selection individuals of population is used for the next generations. Also arithmetic cross over as cross over function and non-uniform mutation in mutation operators are accepted. The controller parameters are regulated for the hardest conditions.

The clearance time of critical error (CCT) is used for setting of controller parameters, without losing its ability to reconstruct the steady state performance, for every disturbance to the system that may act. Computational flowchart is shown for proposed design method in Fig. 5. A very important point that is effective more or less on the optimal solution is the range of unknowns. To run the most basic programs can be offered a broad solution space and after obtaining a solution, the solution space can be considered more limited and closer to the values obtained in the previous repeat. In this paper, there is a range for used gain unknown and time constants parameters and the TCSC controller optimized parameters in Table IV are presented. For a three phase fault applied at bus 7, that it is removed with removal of line between bus 5 and bus 7, Maximum amount of clearing time of error TFC, is obtained 0.152 S according to the algorithm presented in Fig. 4, while CCT without TCSC controller is 0.134 S. Note that the CCT is less than its value in the table (2), without the TCSC controller. Results in Table (2), is obtained by using a simplified method of state variable. However, for the purpose of the sim-ulation has been used a more detailed model by using equations 1 to 9.

Table 3. Used Parameters in GA

parameter	type/quantity
Max. production	100
Population size	50
Selection type	Normalized geometric(00/08)
Cross over type	Arithmetic
Mutation type	Non uniform (2 100 3)
Final method	Max. production

Table 4. Range of unknown variables and optimized parameters

Parameters	Gain KP	Time constants	
		T1	**T2**
Min. of domain	10	0.01	0.01
Max. of domain	70	0.5	0.5
Obtained parameters	30.539	0.3861	0.1719

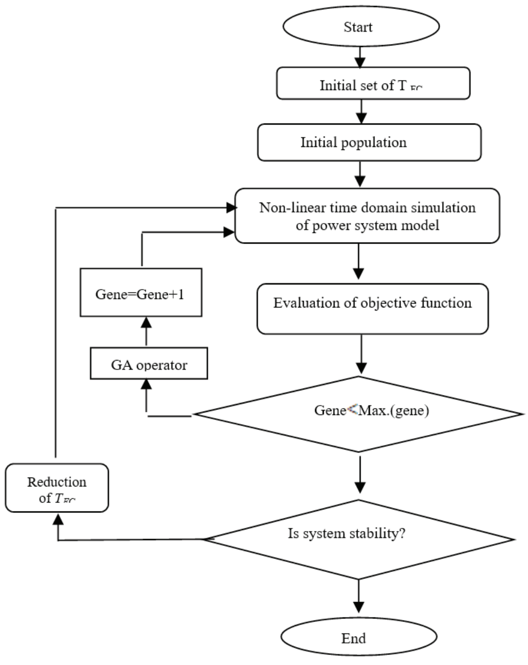

Figure 5. Flowchart of proposed method in GA

Simulation Results

To evaluate the effectiveness the proposed controllers, simulation studies are run for the hardest conditions error (a three phase fault applied at bus 7 and it is removed with removal of line between bus 5 and bus 7). Maximum amount of clearing time of error (TFC =0.152 S) is used in all simulations. Power angle response without and with TCSC controller under this severe disturbance in Figs 6-9 is shown.

Changes associated with speed oscillations related to machines Nos. 2 and 3with TCSC controller is shown in the Figs. 8 and 9. Also Changes associated with speed oscillation response of machines Nos. 2 and 3 with TCSC controller is shown in the Figs. 10 and 11 respectively. These figures show the most important advantage of the TCSC controller genetic optimization not only retaining the transient stability, but also provides good damping characteristics to low frequency oscillations by very quickly stabilization of system. For without Compensator situations TFC is reduced from 0.152 S to 0.134 S, in this situation, without the TCSC controller, the system enables to remain stable. With a similar event (a three-phase fault applied at bus 7, that it is removed with removal of line between bus 5 and bus 7) the simulation is run and the system power angle response without the controller is shown in Figs. 12 and 13.

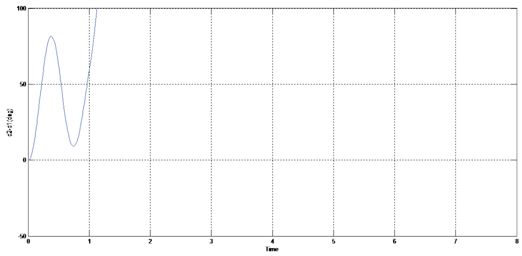

Figure 6. Power angle response of machine 2 without TCSC controller

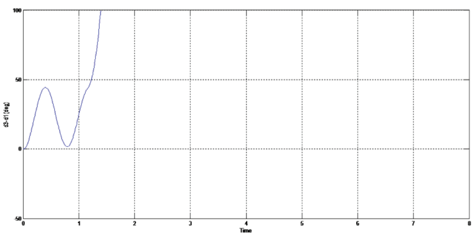

Figure 7. Power angle response of machine 3 without TCSC controller

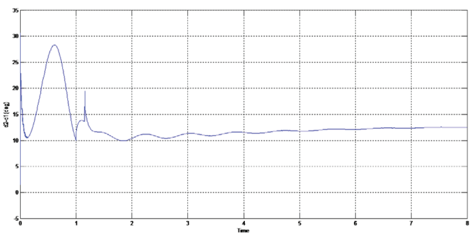

Figure 8. Power angle response of machine 2 with TCSC controller

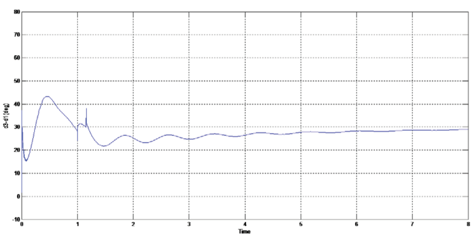

Figure 9. Power angle response of machine 3 with TCSC controller

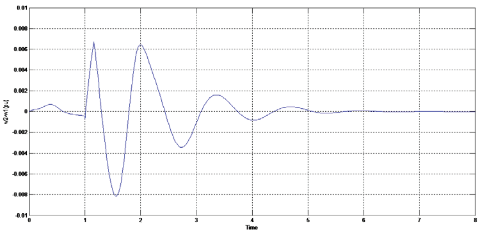

Figure 10. Speed oscillation response of machine 2

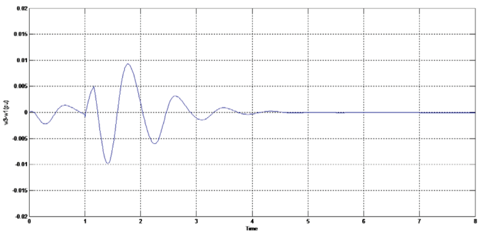

Figure 11. Speed oscillation response of machine 3

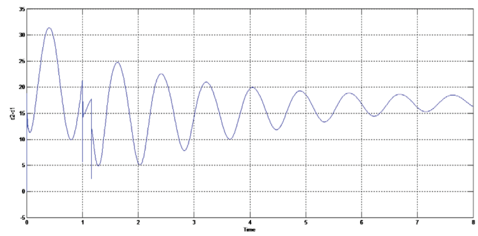

Figure 12. Response of the power angle of machine 2 for time reduce of fault (TFC=0.134)

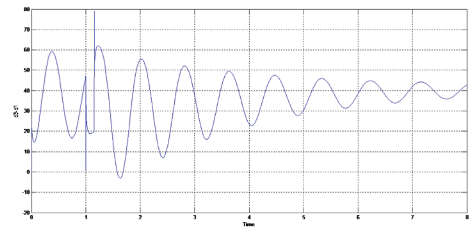

Figure 13. Response of the power angle of machine 3 for time reduce of fault (TFC=0.134)

CONCLUSION

In this paper, a method is presented for modeling and parameters setting of TCSC controller in multi-machine power system to improve transient stability. Initially location of TCSC controller is obtained from the viewpoint of improving the system transient stability, then a simple model of the TCSC controller transfer function is provided to improve stability and then the proposed controller parameters are setting as optimal. Minimization of rotor angle error due to a severe disturbance has been proposed as an optimization problem and TCSC controller optimal parameters are obtained by genetic algorithm. TCSC controller efficiency is tested on a three machines and nine buses power system for the most difficult situation, which is called critical error clearing time. Nonlinear simulation results, the effect of TCSC controller clearly offers increasing of critical error clearing time in system and damping of power system oscillations.

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