

## Thermodynamic model of one of the super heaters and the related spray in the Nekka power plant and Presenting SCO method to control boiler temperature

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**Abstract:** In this paper, first the thermodynamic model is presented to one of the super heaters and sprays of the Nekka power plant and then its unknown parameters are identified according to the registered data of the power plant. SCO control method is introduced to control the external steam temperature of super heater. Finally the conventional method in power plant for controlling external steam temperature of super heater is compared with new method and their performances are presented..

**Keywords:** control, super heater, spray modeling, SCO method

### 1. INTRODUCTION

Various studies have been performed for describing of modern control strategy for controlling power plants. Nakamura *et al* [1, 2, and 3] have worked on the optimized regulators; the static identification of the system is used for applying matrix-vector model. Wallace and Clarke [4] used Kalman filtering for control of power plants. Cori *et al* [5] performed a work called practical optimal control with drum boiler on the power plant. The work was performed based on *LQS* with an additional feedback loop to compensate noise and nonlinearities a study was performed by Surgenor [6, 7] in Australia through comprehensive simulation of boiler in a power plant. This study compares the performance of *LQS* with that of *GMC*.

Nekka heating power plant contains four 440 MW units installed by Bab cock Co. in the last of 1970 and is one of the plants whose steam generators are once-through. Since the steam temperature in different Parts of boiler super heater should be constant, a good controller needs to control the temperature.

In 2<sup>nd</sup> section, a simple and analytical model based on thermodynamic relations is presented to one of the plant super heaters and the related spray and then parameters of these models are obtained by adapting the available data with the real values and then the accuracy of models will be studied.

In 3<sup>rd</sup> section, SCO method [8] to control of the external steam temperature is introduced and applied on one of the super heaters and its corresponding sprays and simulates regardless of other units of the plant.

In 4<sup>th</sup> section, performance of conventional method and SCO is compared by simulation.

### II- Modeling

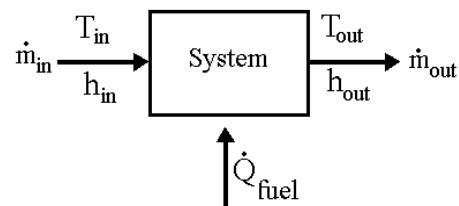
There are different methods for modeling of systems. Since in the plant accessing to inputs to change them or make them stable was not permitted because at security reasons, the identification method based on input-output is not possible using the methods of transfer function and state space, especially that the most parts of the plants are multi-variable. But based on the science of thermodynamic, an appropriate model can be obtained for the plant components (at least around work point) [9]. Using the process by engineering, thermodynamic ideas and heat-transfer obtained model in the

contrast with transfer function models, establish a correct in understanding of internal thermodynamic process.

This section we investigate the thermodynamic process in line 3 of super heater no. 4 in unit 2 of the Nekka power plant and the related spray and provide a model for them.

#### II-I- Super heater

The boiler super heater, ignoring of the losses can be considered as figure 1:



**Figure 1:** Boiler super heater

We know the relation between energy values as:

$$Q_{in} + Q_{Fuel} = Q_{out} \quad (1)$$

By differentiation of the above equation we have:

$$\frac{\partial Q_{in}}{\partial t} + \frac{\partial Q_{Fuel}}{\partial t} = \frac{\partial Q_{out}}{\partial t} \Rightarrow \quad (2)$$

$$\dot{m}_{in} h_{in} + \dot{m}_{in} \dot{h}_{in} + \dot{Q}_{Fuel} = \dot{m}_{out} h_{out} + \dot{m}_{out} \dot{h}_{out}$$

Where  $h=C_p.T$ , since in super heater, the steam temperature increases on constant pressure, and idiomatically the steam is superheated and since the enthalpy dynamic of input steam to the converter relative to other variable such as fuel is trivial, so in above equation  $\dot{h}_{in} = 0$  is assumed. In addition,

$\dot{Q}_{Fuel}$  is the heat obtained from the fuel combustion and obtained from the following equation.

$$\dot{Q}_{Fuel} = \dot{m}_{Fuel} \times CV \quad (3)$$

Where  $C_V$  is the calorific value of the fuel Based on the kind of heating converter inside the boiler and its interval from the burner, the amount of heating obtained from fuel combustion is different and only some part of the fuel energy reaches it. This issue is considered adding a coefficient:

$$\dot{Q}_{Fuel} = \alpha \cdot \dot{m}_{Fuel} \times CV \quad (4)$$

Now the equation of heat equilibrium is simplified to:

$$\dot{m}_{in} \cdot C_p \cdot T_{in} + \alpha \cdot \dot{m}_{Fuel} \cdot CV = \quad (5)$$

$$\dot{m}_{out} \cdot C_p \cdot T_{out} + \dot{m}_{out} \cdot C_p \cdot \tau \cdot \frac{dT_{out}}{dt}$$

Where,  $\tau = \frac{m_{out}}{\dot{m}_{out}}$  is time constant.  $m_{in}$  is the mass of

steam and instruments inside the super heater and is often constant. However,  $\dot{m}_{in}$  is steam flow which depends on the load of plant and is varying. Assuming that input and output steam flow are equal, we have:

$$T_{in} + \alpha \cdot \frac{\dot{m}_{Fuel}}{\dot{m}_{in}} \cdot \frac{CV}{C_p} = T_{out} + \tau \frac{dT_{out}}{dt} \quad (6)$$

Therefore, it can be written:

$$T_{out} = \frac{1}{1 + \tau \cdot S} (T_{in} + K \frac{\dot{m}_{Fuel}}{\dot{m}_{in}}) \quad (7)$$

This first order model can be used as a simple and proper model for boiler subsystems; in this model the value of  $K$  should be identified as a model parameter.

The steam flow entering the super heater equals the sum of the steam entering the spray and the water sprayed on it. Regarding the position of super heater, delay in direction of fuel and flow, and external temperature was individually 10 seconds. (The possible sampling time was 5 seconds.)

$$T_{out} = \frac{1}{1 + \tau s} \left( T_{in} + 1.2 \frac{Fuel}{W + W_s} - 279 \right), \tau = \frac{2000}{W + W_s} \quad (8)$$

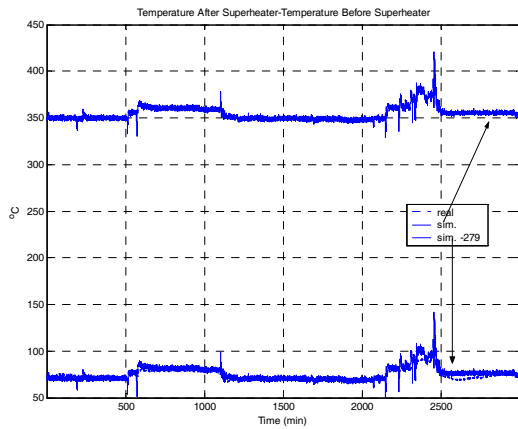


Figure 2: Comparison of Super heater Model with reality

Figure (2) shows amount of increasing water temperature by super heater. Also we are drawing  $1.2 \frac{fuel}{W + W_s}$  for

comparing. This equation was obtained along with try and error, so that the mentioned charts are the same, irrespective of offset. It is observed that there is about 279 degree offset, which derives from implicit linearization of transferring energy equation from the process of fuel combustion to steam,

so the equation  $1.2 \frac{fuel}{W + W_s} - 279$  is correct for

modelling the temperature promotion by super heater. The value of time constant  $\tau$  in above equation is found in such a manner that finally the resulted chart is similar to the

registered data in power plant regarding transient response.

The error of model in many operation points is less than 5 °C (figure 3). The error is observed at the point of load change especially in loads less than 70%, and according to figure 4, the model is appropriate for loads higher than 70% and the mentioned error is less.

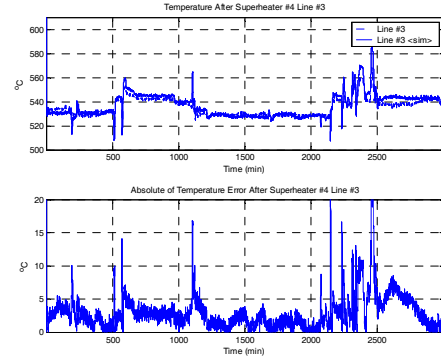


Figure 3: Actual and simulated steam temperature, Absolute error between them

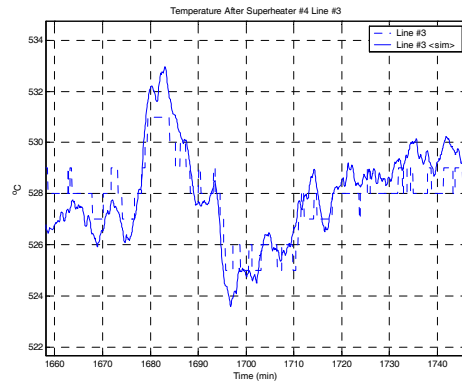


Figure 4: Super heater output steam temperature

## II-II- Spray

In order to stabilize the external steam temperature from super heater, a spray is placed on entrance of super heater. Function of spray is cooling down of input steam, in order to fix temperature in output of super heater. For the output steam temperature from spray  $T_o$ , we will have:

$$\Delta T_o = \frac{1}{C_p} \Delta h_o \quad (9)$$

$$\Delta h_o = \frac{(\bar{h}_i - \bar{h}_o)}{\bar{W}_o} \Delta W_o + \frac{\bar{W}_i}{\bar{W}_o} C_p \Delta T_i - \frac{(\bar{h}_i - \bar{h}_s)}{\bar{W}_o} \Delta W_s$$

This equation is so complex and because only temperature is available and thermodynamic tables are needed to calculate enthalpy and  $C_p$ , they will not calculate easily. We regarded a simple model for it which indicated an acceptable response. In the following this model is described.

If two liquid with rates of flow  $W_i$ ,  $W_s$  and temperatures  $T_i$ ,  $T_s$  are mixed, irrespective of dynamics ruling the process, the following equation can be written for their heating equilibrium temperature:

$$T_{out} = \frac{T_i W_i + T_s W_s}{W_i + W_s}, \quad W_o = W_i + W_s \quad (10)$$

If  $W_i$  is the steam flow and  $W_s$  is the sprayed water flow,

because their  $C_p$  and  $C_v$  rates are different and the internal energy of water is less than steam, the effect of its cooling is more; generally the following model is considered to the spray:

$$T_{out} = \frac{T_i W_i \alpha + T_s W_s}{W_i \alpha + W_s} + \theta, W_{out} = W_i + W_s \quad (11)$$

The above model is completely static and the dynamics and delay were disregarded! The value of  $\alpha$  has been considered for regarding effect of cooling. The base of perform is that the flow of sprayed water involves in heating equilibrium equation more than the real rate.  $\theta$  is a number for correction and it is clear that the amounts of  $\alpha$  and  $\theta$  are different depending on the amount of load. The temperature of output water from spray has been shown in the figure (5):

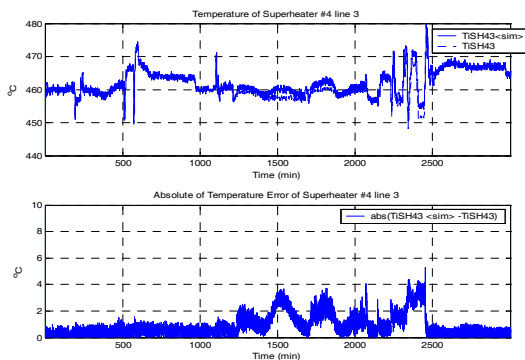


Figure 5: Actual and simulated spray output steam temperature, Absolute error between them

In figure (5), the absolute value of the difference between the temperature of the output steam of spray and the simulated values has been shown. For all loads higher than 70%, this error is less than 2°C.

Figure (6) shows some parts of the mentioned temperature figure in the high load. We can observe a good fitting.

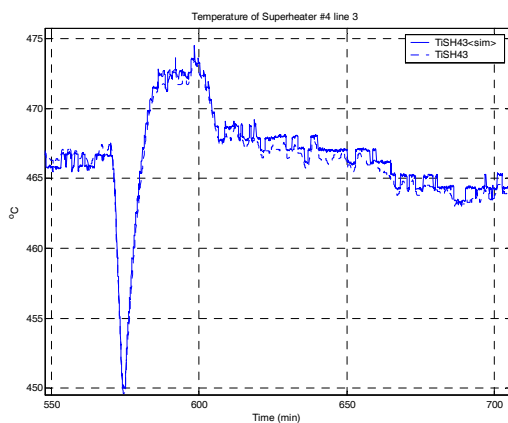


Figure 6: Actual and simulated spray output steam temperature

These models are often valid in higher loads; because of facing summer season and yearly peak consumption in north of the country, the registered data in the Nekka power plant were often higher than 70% and state of power plant was so severe.

III- SCO controller, an appropriate alternative

One of the important parameters of boiler is its temperature

performance. The deviation of temperature from the designed rate should be minimum, especially at the time of load changing. In this case the common cascade controlling methods will not be appropriate for controlling the temperature of super heaters, because this model causes high oscillations in output steam when the load changes. Using the idea of "Two-loop feedback control" or using observer we will have good controlling result.

It is more than one hundred years that controllers  $P$ ,  $PI$  and  $PID$  are used for industrial process. Nevertheless, sometimes controlling of the process have some problems that using some more intelligent methods become clearer. Using "State controller with observer" is one of these methods. In state controllers, not only the input and output of the system but also middle variables are needed. Sometimes there are not middle state measurements, so the observer should calculate them.

Using the states will cause that the system becomes completely stable and its oscillation is prevented. In this case higher gain coefficients can be used.

In 1970s, Lon Berger presented an idea for observers so that by using a mathematical method, middle states are obtained from the process output and input. The process output is compared with the output of a real process and its difference is used to correct the model continually.

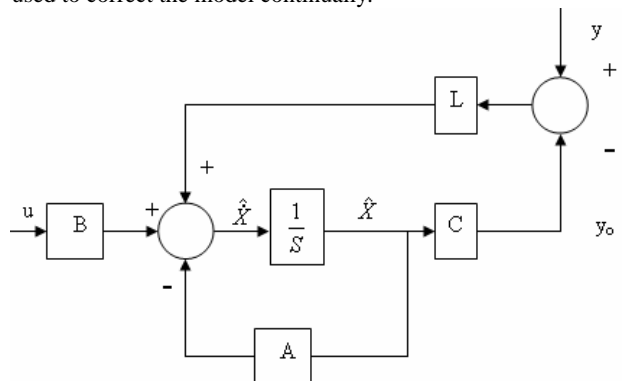


Figure 7: Structure of an observer

Since dynamic behavior of the power plant differs in different loads, so the change of load should be considered and the models used in SCO controller should be changed so that the desired performance is obtained.

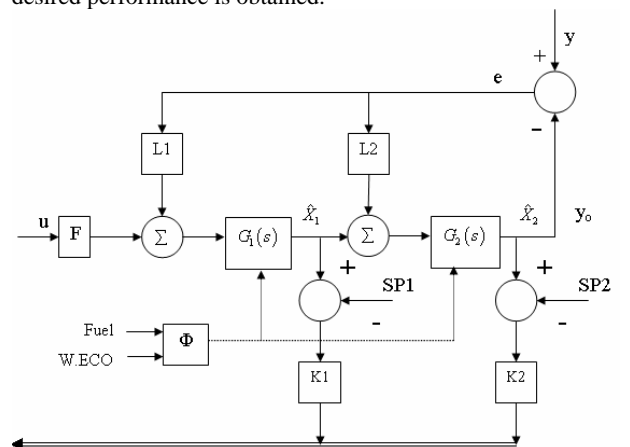


Figure 8: Observer with state feedback (Used in power plant)

In power plant the observer is designed in terms of engineering view! For example instead of state space with

more dimensions it is tried that the system is controlled by limited states. It can be performed easily. For simplicity first regard a middle temperature for the super heater. The controlled system can be shown through two series subsystems, so that the first output is middle temperature and the second output is the external temperature. By doing so, instead of  $n$  state of the system, 2 important states is estimated (figure 8). It can be developed and the system can be divided into 3, 4, ... series subsystems. Knowing the value of fuel flow and the water passing from economizer, the effect of load change is applied by block  $\Phi$  on observer model.

The values of scalars  $L_1$  and  $L_2$  have same function of vector (or matrix) of observer  $L$  in state space. Through output error back propagation, they try to close the product of subsystems to the real system or the error declines towards zero.

$$\begin{bmatrix} \hat{X}_1 \\ \hat{X}_2 \end{bmatrix} = \frac{1}{1 + L_2 \cdot G_2 + L_1 \cdot G_1 \cdot G_2} \begin{bmatrix} F \cdot G_1 \cdot (1 + L_2 \cdot G_2) & L_1 \cdot G_1 \\ F \cdot G_1 \cdot G_2 & L_2 \cdot G_2 + L_1 \cdot G_1 \cdot G_2 \end{bmatrix} \begin{bmatrix} u \\ y \end{bmatrix} \quad (12)$$

For stability of the mentioned observer, it is necessary that at least two equations related to two loops existed, don't have positive roots:

$$1 + L_2 \cdot G_2 + L_1 \cdot G_1 \cdot G_2 = 0 \quad (13)$$

$$1 + L_2 \cdot G_2 = 0$$

Simple first order transfer functions around operating point for subsystems are considered, so that their product can model the super heater approximately. Then for these first order subsystems, the values of  $L_1$  and  $L_2$  are obtained in such a manner that the mentioned relations have fast and stable poles. The summary of *SCO* suggested structure for the controller of super heater temperature will be as follows.  $M$  feedback is used to prevent the severe changes of input temperature of super heater.  $K$  feedback controls middle temperature and external feedback regulates the output temperature of super heater.  $M$  feedback cause linearization of the spray and increases external controller *PI* gain. By using observer and  $K$  feedback, over shoot of output signal is decreased.

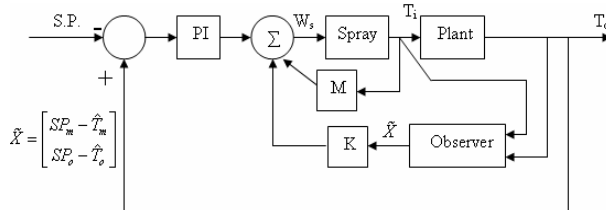


Figure 9: Structure of *SCO*

III-I- The simulation of *SCO*

To obtain *SCO* controller so that the effect of load change doesn't effect it, we proceed as follows:  
First the difference of output and input temperature of the super heater is obtained according to the registered data and thermodynamic equation of the model.

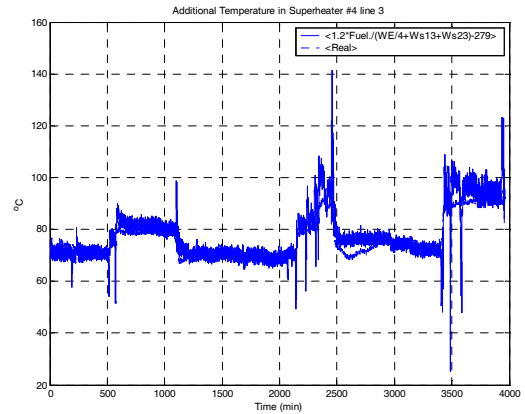


Figure 10: Difference temperature between input and output of super heater

According to thermodynamic relation we have:

$$T_{out} - T_{in} = 1.2 \frac{Fuel}{W + W_s} - 279 \quad (14)$$

Because we are not aware of the water passing from the super heater at the time of controlling, so according to figure (10) a new relation is obtained from economizer in terms of passing water flow, so that it has a good fitting in the chart of temperature difference:

$$T_{out} - T_{in} \approx 56 + \frac{Fuel}{W \times 1.05 + 5} - 279 \quad (15)$$

This relation is divided by 2 and is used to improve two series subsystems at the time of load change.

In the continuation of designing the controller it is assumed that super heater dynamic is indicated with two series systems of  $G_1$  and  $G_2$  in which the effect of load change was regarded using fuel flow and consumption water. 10 second delay of thermodynamic model was divided into 2 parts and for each of them 5 seconds was regarded. The amounts of  $L_1$  and  $L_2$  are 10 and 20, respectively. The roots of equations (13) are stable as is ideal for an observer. (The model pole is  $-0.0333$ ).

$$G_1 = \frac{1}{30S + 1}, \quad G_2 = \frac{1}{30S + 1} \quad (16)$$

$$delay = \frac{1 - 2.5S}{1 + 2.5S}, \quad L_1 = 20, L_2 = 10$$

$$1 + L_2 G_2 = 0 \Rightarrow s = -0.3667$$

$$1 + L_2 G_2 + L_1 G_1 G_2 = 0 \Rightarrow$$

$$s = -0.2745, -0.1255, -0.0333$$

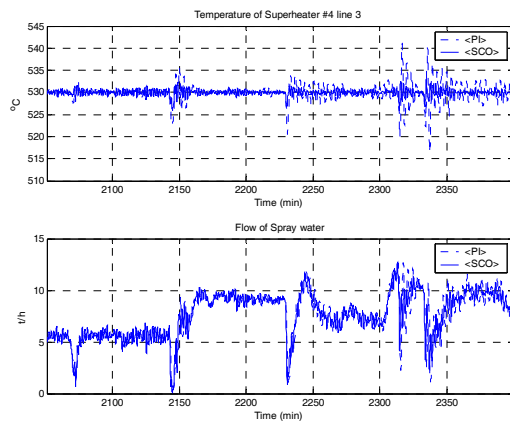
According to figure (8), the amounts of  $K_1$ ,  $K_2$  and  $M$  are 0.1, 0.2 and 0.02, respectively. To regulate the external temperature, the conventional *PI* controller is used. Of course its signal control has been tripled! In the previous method this gain leads to instability. However, *SCO* makes it possible to increase the controller gain. Consequently the rate of response to reference input changes, and the rate of removing the disturbance effect increases.

The purpose was that the out temperature is fixed in 530 °C which it is accomplished easily to fix input temperature in 460 °C and middle one in 495 °C.

IV- Studying the performance of controllers

Both conventional controllers and *SCO* was used and results

were depicted for comparison.



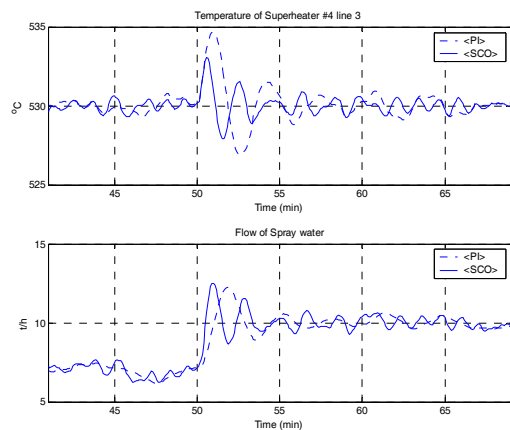
**Figure 11:** Comparison of super heater output temperature and sprayed water flow

Super heater output temperature through conventional control faces with severe overshoot at the moments of load change, but the response of *SCO* controller is good. Because the range of output temperature fluctuations has been reduced, the range of operation error is less than  $0.5\text{ }^{\circ}\text{C}$  (Figure 11).

The conventional controller has a good response to loads higher than 70% and should be regulate for low loads again but in *SCO* controller change of load has been considered in the controller (figure (9)). In figure (11), when the load is reduces from 425 MW to 225 MW step by step, it is obvious that by changing the load and consequently system dynamics the fluctuations in the temperature of the super heater controlled with *PI* will increase, but *SCO* controller, controls the output temperature well.

In figure 12 a disturbance as a sudden promotion of fuel flow at the rate of 3000 tons/hour has been executed.

At the moment to disturbance flow of the fuel was 103650 tons/hour. It is observed that because in the methods of *SCO*, loop gain increases several times, so *SCO* controller increase disturbance rejection.



**Figure 12:** Comparison of super heater output temperature and sprayed water flow

We know that by increasing the loop gain, the effect of noise will be increased. Regarding that the existence of controller loops in the *SCO* several methods will increase the effect of noise, and then an appropriate filter in loop should be used. This controller is robust against dynamic changes. For example at the time of studying response to load change, it has

been seen by changing operation point and dynamics of controlled system, the response of system doesn't have any critical change.

### V- Conclusion

The special properties of *SCO* controller in steam power plant can be stated in summary:

The response of these controllers is very fast, because middle states are involved in controlling. The deviation from ideal temperature is very little and causes the life span of parts servicing.

The slope of load can increase in boiler because there is no concern about temperature controlling. Automatic controlling of temperature is possible at the time of start up. Since controller exploits a model for controlling that concurs with the system and controlling coefficient are regulated intelligently and fits with the load and conditions of controller after cleaning the boiler there is no need for re-optimization. This property leads to suggest the *SCO* to control the boiler temperature.

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