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Fast and Optimized Hydro-Thermal Coordination Scheduling

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Abstract--**In this paper, TENAGA NASIONAL BERHAD (TNB), Malaysian Giant Power Company, real generation data has been undertaken, refined, applied and implemented, the size of the TNB generation system problem is relatively large. The system comprises 53 thermal units and 10 hydro plants of 37 generators. LaGrangian Relaxation (LR) technique, Datzig-Wolf Linear Programming, Sub-Gradient Method (SGM) and Branch & Bound (B&B) have been used to relax the LR multipliers for demand and reserve requirements, and decompose the problem into unit-wise initially and thermal and hydro sub-problems finally. The multipliers are then updated at the lower bound level by SGM. B&B along some heuristics is also used to get a feasible schedule in the hydro-thermal coordination system. The heuristics used here is based on programming with C language code that simplifies on/off statuses of Units for Commitment (UC) and de-commitment scheduling. The required optimum cost and computation time have been achieved.**

Key words--**Power System Operations, Unit Commitment, Dynamic Economic Load Dispatch, Hydro-Thermal Coordination, LaGrangian Relaxation (LR), LaGrangian Dual Problem, LaGrangian Multipliers, Maximum Loading rate, Minimum De-loading rate and Sub-Gradient Method (SGM).**

I. INTRODUCTION

SYSTEMATIC hydro-thermal coordination of the operation of a system of hydroelectric generation plants is usually more complex than the scheduling of thermal generation system. The reason is both simple and important. That is, the hydroelectric plants may be coupled both electrically (as both hydro and thermal systems serve the same load) and hydraulically, as the water outflow from one plant may be a very significant portion of the inflow to one or more other plants located down stream as shown in [1],[2]. Nowadays, hydro-thermal coordination can be solved with the help of several available techniques, in the literature, only LR has been reported to handle systems that consists of medium and large-scale generation systems as shown in [3]-[11]. LaGrangian Relaxation (LR) dual problem is applied in [3] to short-term hydro-thermal coordination unit commitment problems along with fuel constrained units. The authors targeted the solution of the excessive reserve from which upper bound was used in this regard. In [4],[5] LR method is used in two consecutive papers, part one deals with LR problem formulation while part two gives LR dual problem formulations. In the case of [6],[7] , LR is applied to sequential UC and Unit De-commitment methods for the solution of the short-term hydro-thermal coordination problems. Augmented LR method is used in [8] within the principles of LR technique to seek the solution of short-term hydro-thermal coordination problems. LR Dual problem is presented in [9] for Solving Hydro-thermal Scheduling Problems. LR solution technique is applied in [10] for the short-term hydro-thermal coordination problems and presented LR dual problem to come up with dualized sub-problems to the solution of the problem. However, the LR technique has two drawbacks [10], i.e., it cannot find an optimal solution if the targeted problem is non-convex and has dual gap. The contribution among others in this work is to critically interact the TNB data and make critical comparison between this work and that of TNB using the mentioned methods.

II. DYNAMIC ECONOMIC LOAD DISPATCH (DELD)

The generation cost, F_i, of unit i, must be optimized to get the optimized generation cost, F'_i, of unit i. This cost changes from one value to another with the related periods that under goes dynamic process till it reaches the required optimization. The adopted standard dynamic economic dispatch can be described mathematically as follows:

Objective function $= \sum^N{}_i F_i (P_i) + Fsc_i$

$$F'_i = \sum^N{}_i F_i (P_i) + Fsc_i$$

Or $$F_{Ti} = \Sigma_j^T\{\Sigma_i^N (b_i + c_i^j P_i^j + Fsc_i(Tsd_j) + Fsd_j)\} \quad (1)$$

where

$b_i = \Sigma_j^T\{\Sigma_i^N b_i\}$ constant part of the generation cost.

$c_i = \Sigma_j^T(\Sigma_i^N c_i)$ linear part of the generation cost.

Objective function = F'_i, the cost of unit i that will be optimized.

F_i = generation cost function of unit 'i'.

Fsc_i = startup cost of unit 'i'.
F_{Ti} = total generation cost of individual units, i.
Subject to: constraints expressed in (2)-(9). The power output of generators must satisfy the load demand, system spinning reserve and the network losses as:

$$\sum_i^N P_i^j \geq P_{Dj} + P_{Loss} + S_{Rj} \quad (2)$$

where
P_i = output power level of unit 'i'.
P_{Dj} = forecasted power demand in period j.
S_{Rj} = forecasted system spinning reserve
P_{LOSS} = network losses of the system.
Units must be within their max-min limits as:

$$Pi^{min} \leq Pi \leq Pi^{max} \quad (3)$$

Pi^{min} = minimum generation limit of unit 'i'
Pi^{max} = maximum generation limit of unit 'i'
Loading and de-loading rates of a unit must be observed as:

$$P_i^j - P_i^{j-1} \leq \delta P_i^+ T_j \quad (4)$$

δP_i^+ = maximum loading rate of unit 'i'

$$P_i^j - P_i^{j-1} \leq \delta P_i^- T_j \quad (5)$$

δP_i^- = minimum de-loading rate of unit 'i'
δP_i^+ = minimum loading rate of unit 'i'
The online spinning reserve contribution is:

$$\sum S_i^j \leq k_i P_i^j \quad (6)$$

$$S_i^j \leq P_i^{max} - P_i^j \quad (7)$$

Total spinning reserve contribution must be greater than the forecasted system spinning reserve constraint as:

$$\sum S_i^j \geq S_{Rj} \quad (8)$$

where
ΣS_i^j: the summation of all spinning reserve contribution carried by the online generating units.
S_{Rj}: the system spinning reserve forecasted.
Import/export transaction constraint can be modeled as

$$-I_G^{max} \leq \Sigma_{i=1}^{NG} P_i^j - P_{DG}^j \leq E_G^{max} \quad (9)$$

for all g, j g =1,..., NG
Where
I_G^{max}: limit of import group level.
E_G^{max}: limit of export groups.
P_i^j : output power of the generation system in period j.
P_{DG}^j : the power demand of the group in period j.

A. LaGrangian Dual Problem

The aim here is to decompose the problem into original objective function and a new one using the balance and spinning reserve constraints. The balance between output power and demand relaxation, λ along with and spinning reserve relaxation term, μ must comply their limits and other constraints. LR dual problem decomposes the following equations for this purpose.

$$\text{maximize } F(\lambda, \mu) \text{ with all } \mu_j \geq 0 \quad (10)$$

Where

$$F(\lambda, \mu) = \text{minimize}_{\lambda,\mu} \Sigma_j^T\{\Sigma_{i=1}^N F_i(P_i) + Fsc_i - \lambda_j(\Sigma_i^N P_i^j - P_{Dj} + S_{Rj} + P_{LOSS}) - \mu_j[\Sigma_{i=1}^N P_i^{max} - (P_{Dj} + S_{Rj})] \quad (11)$$

where

$$P_i^j - P_{LOSS} = P_{Dj} + S_{Rj} \Rightarrow P_N^j - P_T$$

subject to:
(2), (3), (4), (5), (7), (8) and (9).
The inequalities, $\mu_j, \lambda_j \geq 0$, bound domains of the dual function, $F(\lambda, \mu)$, such that they should not exceed the objective function of the original problem [11].

B. Sub-gradient Method

Sub-gradient method is used to update the dualized multipliers (dualized constraints). As usual the LaGrangian function for a fixed set of LR Multipliers is a lower bound of the objective function value of the original problem. For that reason, different sets of LR multipliers, ω or λ, of different lower bounds are created [11] and can be defined as.

$$\text{max. } L(\omega) = \text{minimize } [\omega b + \text{min.}_{x \notin X} \Sigma_i^N \{c_i - \omega B_i) x_i\}] \quad (12)$$

which is similar to;

$$\text{max. } L(\lambda) = \text{min. } [\lambda b + \text{min. }_{x \notin X} \Sigma_i^N \{ x_i(c_i - \lambda B_i)\}] \quad (13)$$

$$\text{max. } L(\omega); \omega \geq 0, \omega \leq 0, \text{ or non-restricted} \quad (14)$$

where $\lambda = \omega$ and represents the LaGrangian multipliers to be updated for optimization. This is similar to the LR multipliers condition discussed in [1],[2]. In the sub-gradient technique, the sequence of the relaxation coefficient must not violate the its limitations for updating process. The updating process will go through iteration by iteration till it reaches last one.

C. Dantzig-Wolf (D-W) LP Technique

The adopted LP technique is based on Dantzig-Wolf (D-W) LP decomposition method that has been well known for solving such of problems. D-W decomposition is a cost directive decomposition and is commonly used for structured linear program [1]. It is suitable to constrained economic dispatch problems. Since the problem in this work is constrained dynamic ELD, D-W decomposition technique is used in the last part to optimize the operating cost of the DELD problem. The problem can be expressed in the following equations:

$$\text{minimize } [c][X] \quad (15)$$

subject to

$$[A'][X] = [b_o] \quad (16)$$

$$[T'][X] = [R'] \quad (17)$$

$$[X^{max}] \geq [X]; [X] \geq [0] \quad (18)$$

Or min $\Sigma_{i=1}^N CiXi$ as standard form.
where
[C]: a vector dimension of *n* related to incremental cost.
[X]: a vector of *n* dimension accompanied by the output power generation level.
[A']: a matrix of *m x n* dimension related to the linking constraints (formulated in the previous equations).
[T']: a matrix of *m x n* related to the second adopted dual problem model.
$[b_o]$: a vector of dimension m related to the linking constraints (formulated in the previous equations).
[R']: a vector of dimension *m* related to second dual problem model. The convex domain of the set S, is defined as:

$$S = \{X | T'X = R'; X \geq 0\} \quad (19)$$

And S, has extreme points of domain, V as:

$$V = \{V^1, V^2, \ldots, V^k\} \quad (20)$$

Assuming S being bounded at any point X, in S, can be expressed as convex combination of the extreme points of V^k, X can be expressed as:

$X = \Sigma \lambda_k V_k$

$X = \Sigma \lambda_k = 1;$

$\lambda_k \geq 0$ for all k. (21)

The solution of the sub-problems, new variables of λ_k, which affects cost function of the original problem, is introduced. New parameters f_k and g_k must be produced to create a linkage between the T and R and the related to the dual adopted model and the above formulations implicitly.

$$f_k = CV^k \quad \text{for all k.} \tag{22}$$

$$g_k = AV^k \quad \text{for all k.} \tag{23}$$

The master problem is formed in following way:

$$\text{Min } \Sigma_{k=1}^{N} f_k \lambda_k \tag{24}$$

subject to

$$\Sigma_{k=1}^{N} g_k \lambda_k = b_0 \tag{25}$$

$$\Sigma_k \lambda_k = 1 \tag{26}$$

$$\lambda_k \geq 0 \tag{27}$$

As seen in (25) – (27), the variable, λ_k is the solution of these equations. In addition to that, the solution of X variable that represents the output power levels of generators is the solutions of (15) – (22). The new problem has more columns (variables) than original problem but has fewer constraints (rows) than the original one. The problem had "m" number of linking constraints that consists reserve and import constraints but the new problem gets "m+1" number of these two constraints.

III. HYDRO-THERMAL COORDINATION

In this part, short-term hydro-thermal coordination problems are solved using LR technique with sub-gradient method. Consider a power system with "i" thermal units, "k" hydro units. The objective is to minimize the total generation cost. This minimization is subject to system-wide demand and reserve requirements, and individual unit constraints.

The total ost, $F_i^j (P_{ij})$ and startup costs, Fsc_i^j, are:

$$\text{minimize } \sum_j^T \{\sum_i^N \{ U_i^j F_i^j(P_i) + U_i^j(1-U^{j-1}) Fsc_i(x_i^j)\}\} \tag{28}$$

Subject to:

- Power balance constraints

$$\sum_i^N P_i^j + \sum_k^M P_k^j = P_D^j \tag{29}$$

- Spinning reserve constraints

$$\sum_i^N U_i^j P_i^{max} + \sum_{k=1}^{M} P_k^{max} \geq P_{Dj} + S_{Rj} \tag{30}$$

- Capacity constraints of generating units

$$U_i^j P_i^{min} \leq P_i^j \leq U_i^j P_i^{max}$$

$$P_k^{min} \leq P_k^j \leq P_k^{max} \tag{31}$$

- Water balance constraints

$$V_k^{j+1} = V_k^j + R_k^j - Q_k(P_k^j) \tag{32}$$

- Reservoir level should maintain its minimum and maximum capacities

$$V_k^{min} \leq V_k^j \leq V_k^{max} \tag{33}$$

$$V_k^{j=0} = V_{ik};\ V_k^{T=24} = Vf_k \tag{34}$$

- Minimum uptime constraints

$$(U_i^j - U_i^{j-1})(W_i^{j-1} - Tup_i) \leq 0 \tag{35}$$

where

W_i^j is stated as for all time interval of j: $W_i^j = (W_i^{j-1} + j_p)\, U_i^{j-1}$

- Minimum down time constraints

$$(U_i^j - U_i^{j-1})(V_i^{j-1} - Tsd_i) \geq 0 \tag{36}$$

where V_i^j is defined as for all time interval of j,:

$V_i^j = (V_i^{j-1} + j_p)(1 - U_i^{j-1})$

In the above equations; F_i^j: the cost of thermal generation of unit i for the time interval j. Fsc_i^j : the startup cost of unit i at time interval j.

P_i^j: the generation of thermal unit i at time j.

U_i^j: the commitment status of unit i for interval j.

$$U_i^j = \begin{cases} 1 = \text{unit is on in period j.} \\ 0 = \text{unit is off in period j.} \end{cases}$$

x_i^j : the state variable of unit i at time interval j related to startup cost condition.

Q_k : the water released to the turbine of hydro unit plant k.

V_k^j: the water volume of the reservoir and T is the time horizon (T = 24 hours). The sum of all thermal generation P_i^j and hydro generation P_k^j should equal the system demand P_D^j at each hour, i.e., j=1, T. The sum of reserve contributions of thermal units and hydro units should be greater than or equal to the reserve required at each hour, i.e., j=1,..., T.

Cost can be expressed as follows:

$$\text{minimize } F'_i = \sum_j^{jmax} T_j \sum_i^{Nj} F_i^j (P_i^j) \tag{37}$$

where F'_i: total system production cost of unit, i..

T_j: number of hours in the jth time interval.

F_i^j: the cost function of ith thermal unit.

P_i^j: the generation output of ith thermal unit in jth time.

IV. LAGRANGIAN RELAXATION

Equation (1) is relaxed to decompose the problem into sub-problems. The decomposition solution presented here is incorporated by hydro part. The problem can be relaxed as:

$$\text{Minimize } \sum_j^T \sum_i^N \{ U_i^j F_i^j(P_i) + U_i^j(1-U^{j-1}) Fsc_i(x_i^j)\} + \Sigma_j^T \lambda_j [P_{Dj}$$
$$\Sigma_i^j U_i^j P_i^j - \Sigma_j^T P_k^j] + \Sigma_j^T \mu_j [(\Sigma_i^N P_i^{max} + \Sigma_k^M P_k^{max})$$
$$-(P_{Dj} + S_{Rj})] + \psi^j_{i+1} \tag{38}$$

Subject to: (29),(30),(31),(32),(33),(35) and (36) whereλ and μ power balance and reserve balance multipliers to limit their requirements. ψ^j_{i+1} is a checking factor of any violated committed thermal unit after adjusting λ and μ in period j.

A. *The Solution of Dual Problem*

The dual problem solution in this work is based on:

- For a fixed setting of the LaGrangian multipliers, (λ and μ); F(λ and μ) is solved by the minimization of the right hand side of (38). This proposes for the solution of the primal problem variables.
- Carry out the convergence test of the problem. If all convergence criteria are satisfied, then the dual problem is achieved, otherwise the multipliers will be updated again from the beginning (go to step one above).
- After removing the constant terms from (38), it can be separated into thermal and hydro sub-problems.

These sub problems can be formed separately in the following way:

$$\min.\sum_j^T[U_i^jF_i^j(P_i^j)+U_i^j(1-U^{j-1})Fsc_i(x_i^j) - \lambda_jP_i^j\mu_jU_i^jP_i^{max}] \quad \text{Thermal part} \quad (39)$$

Subject to: (31), (35) and (36).

$$\text{Min.}\sum_j^T[-\lambda_jP_k^j-\mu_jP_k^{max}] \quad \text{Hydro part} \quad (40)$$

Subject to: (31),(32),(33) and(34).

V. UNIT COMMITMENT

The objective function of the unit commitment problem can be expressed as:

$$\text{minimize } z = \Sigma_i^N\Sigma_j^T[(b_iU_i^j + c_iP_i^j) + Fsc_iU_i^j] \quad (41)$$

Subject to.

$$\Sigma_i^NP_i^j \geq P_{Dj} + S_{Rj} \quad \text{for all } j. \quad (42)$$

$$\Sigma^N_{i=1}(U_i^jP_i^{max} - P_i^j) \geq S_{Rj} \quad (43)$$

$$U_i^jP_i^{min} \leq P_i^j \leq U_i^jP_i^{max} \quad (44)$$

$\alpha_i^j \geq U_i^j - U_i^{j-1}$; $\alpha_i^j \geq 0$; $U_i^j \geq 0$; and U_i^j is an integer. For all i, j. (45)

The relaxed minimum- maximum problem can be found by penalizing the constraints (load demand and spinning reserve). Adding new penalty terms to the objective function of the problem alters the constraints to the required limitations after iteration processes.

The problem can be expressed as:

$$\text{maximize}_{\lambda,\mu>0}\ L = \Sigma_j^T(P_{Dj}\lambda_j + P_{Dj}\mu_j + S_{Rj}\mu_j) + \min_{x\notin S}\Sigma_j^T\Sigma^N_{i=1}[(b_i - \mu_jP_i^{max})U_i^j + (c_i - \lambda_j)P_i^j + Fsc_i\alpha_i^j] \quad (46)$$

where

The LaGrangian multipliers, λ_j and μ_j are explained before and can be decomposed into single generator sub-problems as:

$$\text{minimize}_{x\notin S}\Sigma_j^T[(b_i - \mu_jP_i^{max})U_i^j + (c_i - \lambda_j)P_i^j + Fsc_i\alpha_i^j] \quad (47)$$

with the already related constraints of:

$U_i^jP_i^{min} \leq P_i^j \leq U_i^jP_i^{max}$

$\alpha_i^j \geq U_i^j - U_i^{j-1}$

$\alpha_i^j \geq 0$; $U_i^j \geq 0$; and U_i^j is an integer.

where

The minimization function is similar to (38) except the checking factor, ψ^j_{i+1}, associated with the former, and startup/shutdown states, α_i^j is incorporated with the later. The function is decomposed [1,3] into:

$$F(\lambda,\mu) = \text{minimize}_{\lambda,\mu}\ \Sigma_j^T\{\Sigma_i^N U_i^jF_i(P_i) + U_i^j(1 - U_i^{j-1})Fsc_i(\alpha_i^j) - \lambda_j[(\Sigma_i^NP_N^j) - P_{Tj}] - \mu_j[(U_i^j\Sigma_i^NP_i^{max} + \Sigma_k^M P_k^{max}) - (P_{Dj}+S_{Rj})]\} \quad (48)$$

VI. RESULTS AND DISCUSSIONS

Table I presents the power demand throughout Peninsular Malaysia in 24 hours period. Table II shows the hydro plants characteristics consisting of minimum-maximum water discharges from the reservoirs and minimum-maximum generation capacities. Table III presents the unit commitment results of the hydro-thermal coordination system, in addition, the optimized generation cost of hydro-thermal coordination is also presented in this table. Fig. 1 shows the difference between some of this system output levels and that of TNB output levels. These results have a cost saving comparing to the results of power utility hydro-thermal coordination costs. The generation costs saving found in this work is 0.435% compared to the total corresponding figure of the TNB power utility company's results.

Table I: Power Demand by Peninsular Malaysia

HOUR	WEEKDAY MW	SATURDAY MW	SUNDAY MW	SYSTEM SPIN. RESERVE MW
0100	6104	6156	5853	700
0200	5874	5943	5568	700
0300	5739	5794	5397	700
0400	5644	5706	5422	700
0500	5558	5580	5366	700
0600	5809	5632	5343	700
0700	6015	5687	5302	700
0800	6421	6268	5133	700
0900	7521	7241	5355	700
1000	7907	7520	5639	700
1100	8301	8032	5959	700
1200	8334	7767	6024	700
1300	7956	7609	5921	700
1400	8288	7406	5893	700
1500	8387	7173	5965	700
1600	8415	7225	5926	700
1700	8099	7006	5832	700
1800	7513	6497	5659	700
1900	7358	6611	5750	700
2000	7697	7140	6609	700
2100	7453	6954	6429	700
2200	7065	6619	6339	700
2300	6798	6561	6314	700
2400	6274	6100	5990	700

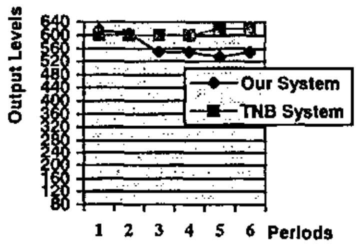
Table II: The hydro Characteristics

Plant	Unit	Q_k^{max} (m^3/s)	Q_k^{min} (m^3/s)	P_k^{max} (MW)	P_k^{min} (MW)
1	4	110	20	125	20
2	4	110	20	94	24.5
3	3	110	20	25.8	2.8
4	3	130	20	40	2.5
5	4	11.4	5	27.7	2.5
6	4	140	30	150	40
7	4	5.6	1	27.6	2.5
8	3	25	4.2	57	5
9	4	68.1	34	10	3.7
10	4	50	15	4.8	2

Table III: The Units Status for Six Periods

PERIOD						
UNIT	1	2	3	4	5	6
U1	1	1	1	1	1	1
U2	1	1	1	1	1	1
U3	1	1	1	1	1	1
U4	1	1	1	1	1	1
U5	0	0	0	0	0	0
U6	0	0	0	0	0	0
U7	1	1	1	1	1	1
U8	0	0	0	0	0	0
U9	0	0	0	0	0	0
U10	0	0	0	0	0	0
U11	0	0	0	0	0	0
U12	1	1	1	1	1	1
U13	1	1	1	1	1	1
U14	1	1	1	1	1	1
U15	1	1	1	1	1	1
U16	0	0	0	0	0	0
U17	0	0	0	0	0	0
U18	0	0	0	0	0	0
U19	0	0	0	0	0	0
U20	1	1	1	1	1	1
U21	1	1	1	1	1	1
U22	1	1	1	1	1	1
U23	1	1	1	1	1	1
U24	1	1	1	1	1	1
U25	1	1	1	1	1	1
U26	0	0	0	0	0	0
U27	0	0	0	0	0	0
U28	0	0	0	0	0	0
U29	0	0	0	0	0	0
U30	0	0	0	0	0	0
U31	0	0	0	0	0	0
U32	0	0	0	0	0	0
U33	0	0	0	0	0	0
U34	0	0	0	0	0	0
U35	0	0	0	0	0	0
U36	0	0	0	0	0	0
U37	0	0	0	0	0	0
U38	0	0	0	0	0	0
U39	1	1	1	1	1	1
U40	1	1	1	1	1	1
U41	0	0	0	0	0	0
U42	0	0	0	0	0	0
U43	0	0	0	0	0	0
U44	0	0	0	0	0	0
U45	0	0	0	0	0	0
U46	0	0	0	0	0	0
U47	0	0	0	0	0	0
U48	0	0	0	0	0	0
U49	1	1	1	1	1	1
U50	1	1	1	1	1	1
U51	0	0	0	0	0	0
U52	1	1	1	1	1	1
U53	1	1	1	1	1	1
PH1	1	1	1	1	1	1
PH2	1	1	1	1	1	1
PH3	1	1	1	1	1	1
PH4	1	1	1	1	1	1
PH5	1	1	1	1	1	1
PH6	0	0	0	0	0	0
PH7	0	0	0	0	0	0
PH8	0	0	0	0	0	0
PH9	1	1	1	1	1	1
PH10	1	1	1	1	1	1

Hydro-thermal costs RM: 10,403,124.0000 for 24 hours.



VII. CONCLUSION

In this work, it has been proved that the hydropower system is very important power generation for generation cost reduction and the increase profit return from generation system. As far as the available techniques used to solve hydro-thermal coordination problems are concerned, this work has demonstrated that the LR and LP technique can solve the problems effectively. The results achieved from the problems used in these techniques show their effectiveness and their optimization capabilities. The most important achievements for using hydro-thermal coordination system is the significant reduction in the total generation costs that is the most important requirements of the power generation utility. This goal has been achieved in this work as shown in the results.

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