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A Novel Stability Model for AC-DC Combined Simultaneous Power Flow

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***Abstract*— Conversion of an already running AC transmission system, with very high voltage and longer length, into a system with the mixed operation of AC-DC can bring the benefit of stability improvement. Of late, most of the developments in stability analysis are simulation based. Sometimes it is difficult to draw a generalized conclusion through simulation result. In this case, an analytical model can be a perfect tool to analyze the fault and get concrete decision about the future planning. In this paper a mathematical equation is exposed which can be applied to determine the stability in case of different types of fault. Primarily, the stability equation is established for the fault at the transmission line and then introducing simple logical modification it can be applicable for the development of analytical models of all kinds of faults, such as; Fault at the load terminal, sustained fault at the line, fault at the line where the generator is located. To expose the efficacy of the developed stability model two different ways of validation process is followed and optimistic results are found.**

***Keywords*— Double circuit transmission, AC-DC combined system, reclosing time, fault clearing time, stability improvement.**

NOMENCLATURE

H	Generator inertia constant
P_{acf}	Flow of power in AC form during faulted condition
P_{comb}	AC-DC mixed flow of power
P_{DCpf}	Post-fault DC power flow
$\bar{P}_{acm}$	Post fault steady AC power
T_{CR}	AC-DC combined system fault clearing time
T_{RC}	Circuit breaker reclosing time
ω_s	Angular frequency
δ_{RC}	Circuit breaker re-closing angle after the fault
δ_{ac}	Power transfer angle for AC current in AC-DC combined system
δ_{CR}	Fault clearing angle for combined AC-DC system
δ_m	Maximum rotor angle

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I. INTRODUCTION

POWER systems networks are becoming more and more complex and it is a great challenge for transferring the electrical power from one place to another. There are some limiting factors in electrical power flowing using a transmission line and among them the stability is the topmost one [1-2]. Application of state of the art technology like FACTS devices can upgrade the loadability and stability both [3-4]. Parallel operation of AC and DC transmission line can increase the stability by a great extent [5-8]. Due to power electronics devices application in this system, the DC line is highly controllable in parallel operation of AC-DC power flow.

Improvement in stability for a long transmission system can be ensured through combined flow of AC form and DC form of power at a time in the same line. Considering the stability issue this power flow technique is equivalent to parallel lines of AC and DC system.

A stability analysis is performed by H. Rahman *et al.*[9] in case of combinatory power flow with AC and SC mixed. The authors have shown that the reduction of rotor speed deviation and damping the power oscillation is quicker in this combined power flow approach compared to that of original AC system with 30% compensation.

A new method of stability analysis for AC-DC mixed power flow line is presented in [10]. In this approach the whole system is considered as a system with pure DC operation when the fault is cleared and it remains in this condition up to the normal steady state operation. When entire the system come into the absolutely normal behaviour the circuit breakers are turned on to flow AC and DC both simultaneously.

The transient stability of a mixed AC-DC simultaneous system is compared with the systems containing static synchronous compensator (STATCOM) and static synchronous series compensator (SSSC) in [11]. It concluded that the combined AC-DC power flow system is superior to the other two systems.

An analytical expression for the analysis of stability in transient fault condition of AC-DC combined system is developed in [12]. The model can give the critical time and angle for clearing the fault, disregarding the conventional trial and error approach. It also gives the expression of critical time for clearing the fault in terms of that of unconverted original AC system.

Stability analysis for a system with long transmission line is greatly depends on the fault types and locations since the power flow scenario during the fault and post fault condition varies with the fault types and locations. The model of [12] is developed considering the fault at the load terminal. The main difficulty of this model is that it is not applicable for the analysis of other kinds of fault. An analytical model of stability analysis is presented in [13]. This model can be applied for all kinds of faults irrespective of locations but the developed expression is large and complex.

This paper presents a generalized stability model in simplified way. The developed model of this paper can be applicable for all kinds of faults and fault locations subject to some minor modifications.

II. Proposed Model

In an AC-DC combined system the mixed AC and DC form of power is flown simultaneously in a same conductor. An analytical expression for the analysis of transient stability of an AC-DC combined system is established in this section. The special feature of the model is that it can be applied for the calculation of critical clearing time for all locations and types of fault. Initially the mathematical equation is developed considering the transient fault at the transmission line and then the generalized feature of the equation is exposed applying some minor modifications.

Fig.1 shows a 3-phase AC-DC combined power flow system with double circuit accommodation. A transient fault is considered in one of the lines which is pointed as F in the figure.

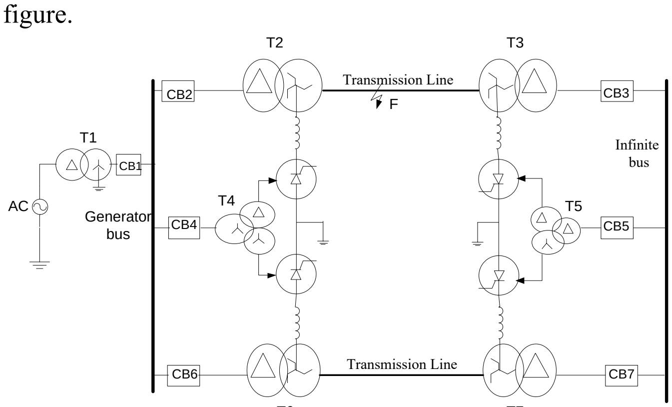

Fig. 1. Double circuit AC-DC mixed power flow system

The fault is occurred at the line and it is not close to the sending end bus; therefore, power will flow with a small magnitude through the other line during fault . Fig. 2 presents the AC-DC combined flow of power during pre-fault, fault and post-fault conditions. P_{acs} and P_{dcs} in Fig.2 represent the AC and DC steady state power of this combined power flow system.

The faulty line is isolated as fast as possible by the circuit breaker operation. The other line will carry the combined power alone with half magnitude soon after the fault is cleared. After certain delay, circuit breaker will reconnect the tripped line and the whole the system will be in full swing operation.

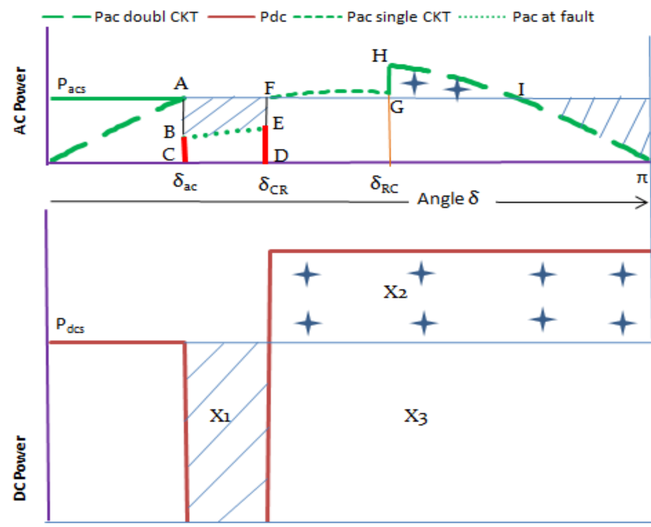

Fig. 2. AC-DC combined power flow diagram

Applying the equal area criterion for the analysis of stability of the aforesaid system the equation of transient stability can be shown from Fig.2 as

$$(P_{comb} - P_{acf})(\delta_{CR} - \delta_{ac}) = \left[P_{DCpf} + \frac{\bar{P}_{acm}}{2}\right](\delta_{RC} - \delta_{CR}) + \left[P_{DCpf} + \bar{P}_{acm}\right](\delta_m - \delta_{RC}) - P_{comb}(\delta_m - \delta_{CR}) \quad (1)$$

Where

P_{comb}= Combined flow of AC and DC power.

= P_{acs}+P_{dcs}

P_{DCpf}= Flow of DC power after fault clearing process

$\bar{P}_{acm}$ = Flow of AC power after fault clearing process

P_{acf}= AC Power flow during faulted condition

δ_{ac}= Rotor angle/torque angle before the fault

δ_{CR}= Critical clearing angle

δ_{RC} = Circuit breaker re-closing angle after the fault

δ_m= Maximum rotor angle

The determination process of steady state AC power, $\bar{P}_{acm}$, during the post fault situation is presented in [12] and the evaluation process of faulted condition power, P_{acf}, is elaborately presented in [13].

It is evident that for a long transmission line the reactance of only the line has the lion share in the combined reactance of the whole system from generator to the receiving end bus. That is, the terminal reactance (reactance of generator and transformer) is very low in comparison with the line reactance. Taking this into account, the equivalent line reactance will be approximately double when a circuit of a double circuit transmission line is in out of service. In that case, the AC power flow through single circuit will be approximately half of the combined steady state power flow of both the lines in combined AC-DC power system.

When a fault appears in a circuit of a double circuit power flow system the circuit breakers of that line clear that fault and during the dead time of the circuit breakers this double circuit line is operated as a single circuit. Due to this fact the power flow in AC form is considered as $\frac{\bar{P}_{acm}}{2}$, in case of single circuit operation, where $\bar{P}_{acm}$ is the double circuit load flow in AC form of this combined AC-DC operation.

Now the expression of critical clearing angle can be obtained from (1) as

$$P_{comb}(\delta_m - \delta_{ac}) = \left[P_{DCpf} + \frac{\bar{P}_{acm}}{2}\right](\delta_{RC} - \delta_{CR}) + \left[P_{DCpf} + \bar{P}_{acm}\right](\delta_m - \delta_{RC}) + P_{acf}(\delta_{CR} - \delta_{ac}) \quad (2)$$

$$or \left(P_{DCpf} + \frac{\bar{P}_{acm}}{2} - P_{acf}\right)\delta_{CR} = (P_{DCpf} + \bar{P}_{acm})\delta_m - P_{comb} + \left(\frac{\bar{P}_{acm}}{2} - \bar{P}_{acm}\right)\delta_{RC} - P_{acf}(\delta_{ac}) \quad (3)$$

$$or\ \delta_{CR} = \frac{(P_{DCpf} + \bar{P}_{acm} - P_{comb})\delta_m - (P_{comb} - P_{acf})\delta_{ac} - \frac{\bar{P}_{acm}}{2}\delta_{RC}}{\left(P_{DCpf} + \frac{\bar{P}_{acm}}{2} - P_{acf}\right)} \quad (4)$$

From (4) it is seen that δ_{CR} depends on δ_{RC}. In calculating the critical clearing time (CCT) of fault, it is necessary to consider the reclosing time of circuit breaker. Now, the equation of δ_{CR} and δ_{RC} can be expressed with respect to T_{CR} and T_{RC}, respectively as

$$\delta_{CR} = \frac{T_{CR}^2\,\omega_s}{4H}\left(P_{comb} - P_{acf}\right) + \delta_{ac} \quad (5)$$

$$\begin{aligned}\delta_{RC} &= \frac{T_{RC}^2\,\omega_s}{4H}\left[P_{comb} - P_{DCpf} - \frac{\bar{P}_{acm}}{2}\right] + \delta_{CR} + \frac{T_{CR}^2\,\omega_s}{4H}\left(P_{comb} - P_{acf}\right)\\ &= \frac{T_{RC}^2\,\omega_s}{4H}\left[P_{comb} - P_{DCpf} - \frac{\bar{P}_{acm}}{2}\right] + \frac{T_{CR}^2\,\omega_s}{4H}\left(P_{comb} - P_{acf}\right) + \delta_{ac} + \frac{T_{CR}^2\,\omega_s}{4H}\left(P_{comb} - P_{acf}\right)\\ &= \frac{T_{RC}^2\,\omega_s}{4H}\left[P_{comb} - P_{DCpf} - \frac{\bar{P}_{acm}}{2}\right] + \delta_{ac} + \frac{2\,T_{CR}^2\,\omega_s}{4H}\left(P_{comb} - P_{acf}\right)\end{aligned} \quad (6)$$

Now, applying (5) and (6) in (3) the stability equation can be shown as (7).

$$\left(P_{DCpf} + \frac{\bar{P}_{acm}}{2} - P_{acf}\right)\left[\frac{T_{CR}^2\,\omega_s}{4H}\left(P_{comb} - P_{acf}\right) + \delta_{ac}\right] = (P_{DCpf} + \bar{P}_{acm})\delta_m - P_{comb}\left(\delta_m - \delta_{ac}\right) - \frac{\bar{P}_{acm}}{2}\left[\frac{T_{RC}^2\,\omega_s}{4H}\left(P_{comb} - P_{DCpf} - \frac{\bar{P}_{acm}}{2}\right) + \delta_{ac} + \frac{2\,T_{CR}^2\,\omega_s}{4H}\left(P_{comb} - P_{acf}\right) - P_{acf}(\delta_{ac})\right] \quad (7)$$

Putting, $M = \frac{\omega_s}{4H}$ and re-arranging the terms of (7) the equation of T_{CR} can be shown as

$$T_{CR} = \sqrt{\frac{\left(P_{DCpf} + \bar{P}_{acm} - P_{comb}\right)(\delta_m - \delta_{ac}) + \frac{\bar{P}_{acm}}{2}\left(+P_{DCpf} + \frac{\bar{P}_{acm}}{2} - P_{comb}\right)M\,T_{RC}^2}{M(P_{comb} - P_{acf})\left[P_{DCpf} + 3\frac{\bar{P}_{acm}}{2} - P_{acf}\right]}} \quad (8)$$

Let, Post fault total steady state power, $P_{TSP} = P_{DCpf} + \bar{P}_{acm}$ and the expression (8) becomes as

$$T_{CR} = \sqrt{\frac{(P_{TSP} - P_{comb})(\delta_m - \delta_{ac}) + \frac{\bar{P}_{acm}}{2}\left(P_{TSP} - \frac{\bar{P}_{acm}}{2} - P_{comb}\right)M\,T_{RC}^2}{M(P_{comb} - P_{acf})\left[P_{TSP} + \frac{\bar{P}_{acm}}{2} - P_{acf}\right]}} \quad (9)$$

The generalized analytical expression of CCT is presented in (9) considering the fault in transmission line. The expression can be applied for all types of fault at any location considering some minor modification which is shown below.

A. Transient fault in a line nearest to the generator bus

If a transient fault occurs very near to the sending end bus the voltage of that bus will be zero and the amount of power flow during fault will also be zero, that is, $\boldsymbol{P_{acf} = 0}$.

In this case the expression of $\boldsymbol{T_{CR}}$ can be shown as (10)

$$T_{CR} = \sqrt{\frac{(P_{TSP} - P_{comb})(\delta_m - \delta_{ac}) + \frac{\bar{P}_{acm}}{2}\left(P_{TSP} - \frac{\bar{P}_{acm}}{2} - P_{comb}\right) M\, T_{RC}^2}{M P_{comb}\left[P_{TSP} + \frac{\bar{P}_{acm}}{2}\right]}} \quad (10)$$

B. For the sustain fault at the transmission system

Whenever a permanent fault appears in a line of the transmission system with double circuit, power can be flown through single circuit only after isolating the faulty line. During post-fault condition the post fault steady state power will be half of the pre-fault power. In equation (9), $\boldsymbol{P_{TSP}}$ will be replaced by $\frac{\boldsymbol{P_{TSP}}}{\boldsymbol{2}}$. In this type of fault circuit breaker reclosing is not possible and hence the T_{RC} will be zero. The CCT expression can be shown as

$$\boldsymbol{T_{CR}} = \sqrt{\frac{\left(\frac{P_{TSP}}{2} - \boldsymbol{P_{comb}}\right)(\boldsymbol{\delta_m} - \boldsymbol{\delta_{ac}})}{\boldsymbol{M}(\boldsymbol{P_{comb}} - \boldsymbol{P_{acf}})\left[\frac{P_{TSP}}{2} + \frac{\bar{P}_{acm}}{2} - \boldsymbol{P_{acf}}\right]}} \quad (\mathbf{11})$$

C. For the fault at the load terminal

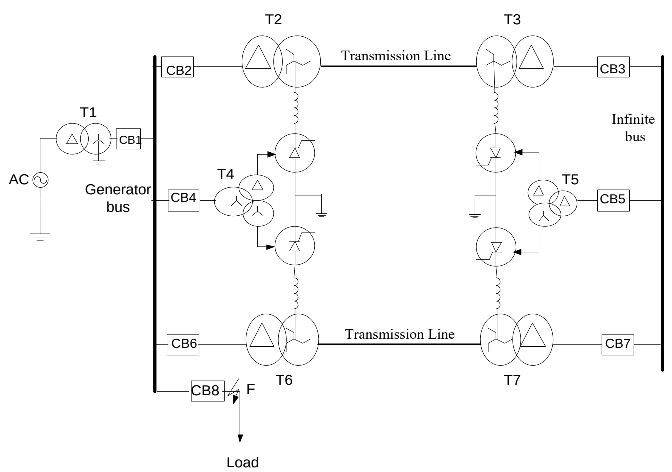

Fig. 3. Load terminal fault close to the generator

Fig. 3 shows a fault occurred at the terminal of load which is very near to the generator bus. In this case of fault the potential at the load terminal would be zero. The following approximation can be made in this case:

i. The power flow will be zero during fault, it means that the value of P_{acf} should be considered as zero.
ii. Circuit breakers and converters of the transmission line will remain at normal condition. As there is no consideration of circuit breaking and reclosing the value of T_{RC} should be zero.
iii. Both the lines of double circuit system will be in service after clearing the fault and there is no option of single circuit power flow which gives $\frac{\bar{P}_{acm}}{2} = 0$.

Applying the above mentioned conditions in (9) the CCT can be shown as

$$T_{CR} = \sqrt{\frac{(P_{TSP} - P_{comb})(\delta_m - \delta_{ac})}{M\, P_{comb} P_{TSP}}} \quad (12)$$

III. Developed Analytical Model Validation

This section extensively justifies the correctness of the analytical expressions which are developed in the previous section. The justification of correctness is performed in two distinct ways. One way, the outcome of the analytical expression is compared with the result published in the literature and the other way, obtained outcome of the expression is compared with the result of circuit simulation considering a real system.

A. Validation using the result published in the literature

In this case, the validation is performed considering the results published in [13]. The authors of the paper produced the result by applying the developed model in IEEE 2nd benchmark system. Appendix A, elaborately figure out the circuit model and the system variables of this system. The developed model of this paper is also applied into the same system considering the same criteria and compared the obtained results with those of [13]

Table I and Table II show the result comparison considering the change in the mixture of voltage and angle of power transmission, respectively. It is noticed that due to the change in the mixture of DC voltage from 20% to 49.5% the greatest difference of 2.1% is found between the results of column 2 and 3 of Table I.

In Table II the results are compared considering the variation of transmission angle from 20 to 60 degree and the results deviations are found from 1.6% to 1.8%. The results comparison in Tables I and II clearly give an idea that outcome of the analytical expressions is not far away from the literature results.

TABLE I
RESULTS COMPARISON OBTAINED THROUGH MIXTURE OF DC VOLTAGE VARIATION

DC voltage mix(%)	Critical Clearing Time (CCT) in millisecond		Difference (%)
	From the developed Model	Published result in [13]	
20	270	266	1.5
30	287	281	2.1
40	294	288	2.0
49.5	295	291	1.3

TABLE II
RESULTS COMPARISON OBTAINED THROUGH THE VARIATION OF TRANSMISSION ANGLE

Angle of Power transmission (degree)	CCT		Difference (%)
	From developed model	Published result in [13]	
20	315	310	1.6
30	307	302	1.6
40	299	294	1.7
50	290	285	1.7
60	281	276	1.8

B. *Validation using simulation of a real circuit*

A real model of a circuit is developed in this section through MATLAB Simulink software considering a 500kV real system which is located at Montana. The circuit simulation is performed for a fault which is considered in the transmission line and it is three-phase to ground in nature. Appendix B presented the detail information about the circuit parameters. The CCT is evaluated considering the variation of the angle of transmission from 20^0 to 60^0 at a particular voltage mix in DC form of 49.5%. The power flow at steady state condition and the circuit breaker reclosing time are considered as 2200 MW and 300ms, respectively. The developed model of this paper is also applied into the same system considering the same parameters. The outcome of the analytical model is compared with the outcome of the real circuit simulation. The comparison of the results is given in Table III. It is clearly seen that the obtained result from the developed model is very much near to the simulation result and the magnitude of the average difference is found as 2.76%.

TABLE III
RESULTS COMPARISON BETWEEN CIRCUIT SIMULATION AND DEVELOPED MODEL

Angle of Power transmission (degree)	CCT		Difference (%)
	From developed model	Using MATLAB simulation	
20	180	180	0
30	167	170	1.76
40	154	163	5.52
50	141	145	2.76
60	128	133	3.76

IV. CONCLUSION

Among the major limiting factors of load flow in a long transmission system the transient stability is the potential one. The simultaneous flow of AC form and DC form of power in the same line in a transmission system, increase the transient stability. A simplified analytical expression for the analysis of stability in case of transmission line with AC-DC mixed load flow system is presented in this paper. The model is so simple and diversified that it can be applied irrespective of locations and types of fault with minor modifications. The power system planners can take this model as an analytical tool.

The model validation through published result gives an indication that the accuracy of the model is very high. The percentage of error varies from 1.3% to 2.1% in comparison with the established results. On the contrary, the validation through circuit simulation also shows a promising result with an average difference of 2.76% between the output obtained from the developed model and simulation result.

APPENDIX-A

IEEE 2nd bench mark system is presented in Fig. 4 and the required data is presented in table IV.

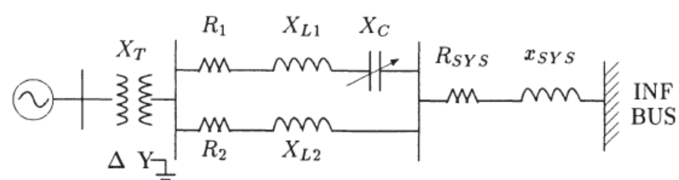

Fig. 4. IEEE 2nd bench mark system

Table IV
SYSTEM PARAMETERS ON 100 MVA

Parameter	Positive Sequence	Zero Sequence
R_T	0.0002	0.0002
X_T	0.0200	0.0200
R_1	0.0074	0.0220
X_{L1}	0.0800	0.2400
R_2	0.0067	0.0186
X_{L2}	0.0739	0.2100
R_{SYS}	0.0014	0.0014
X_{SYS}	0.0300	0.0300

APPENDIX-B

Montana 500 kV transmission system is chosen for the model validation using circuit simulation approach. Electrical power is wheeling through the line from Colstrip to Taft which is shown in Fig. 5[14]. The generation capacity of Colstrip generating plant is 2272 MW which is treated as equivalent machine. The infinite bus is considered at Taft and the buses of Broadview and Garrison are ignored in the presented circuit. The transmission line variables are given in Table V.

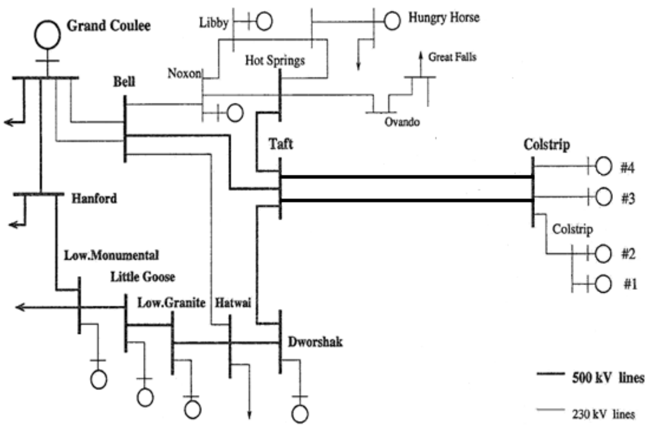

Fig. 5. Montana 500 kV transmission system

TABLE V
SYSTEM PARAMETERS FOR MONTANA 500 KV TRANSMISSION LINE

Sl. No.	Component	Parameter
01	Line	x = j253.21 Ω/phase/ckt, Double ckt, Three phase, 60Hz, 804km'500kV,Thermal limit current = 3kA
02	Generator	358*2, 778*2(MW) 24kV,Reactance=0.3pu, H=3.5 s.
03	Generator Transformer	24/230kV, Leakage reactance = 0.15pu.
04	Transformer (At the sending end of the line):	Δ-Y, 230/500kV, leakage reactance = 0.1pu. (pure AC) Δ-Z, 230/253kV, Leakage reactance = 0.1pu. (AC-DC)
05	Transformer (At the receiving end of the line):	Z-Δ 253/500kV, Leakage reactance= 0.1pu, (AC-DC)
06	DC system	DC system rated voltage and current are 202kVand 9kA, respectively.

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