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Development of a Short Transmission Line Module for Electrical Power Laboratory Application

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Abstract A panel inductor was recovered from an obsolete mercury-arc rectifier and was considered useful for the development of a short transmission line module. A short-circuit test was conducted to determine the possible maximum current of the inductor which was 6.22A at 89V. A rheostat was used to introduce a line loss of 8.33% of delivered power from which the line module resistance was obtained as 1.05Ω. The open-circuit test carried out gave 220V and 205V as the input and output voltages, respectively; showing an exhibition of 15V back residual voltage capacity. For the purpose of load test a 220V, 50Hz, 14A single-phase induction motor was selected to run light drawing 5.12A from the line module at 220V and at 0.293 power factor (lagging). The load current of 5.12A was considered as the line rated and safe full-load current, for which the line module gave a reactance of 27.32Ω. From all the above tests and with the said load power factor, the line module input voltage, transmission efficiency, reactive power delivery and voltage regulation as key parameters were: 360V, 92.31%, 1077VAr and 63.64%, respectively; whereas, if the load power factor were 0.8 (lagging) and the full-load current of 5.12A being delivered at 220V, the values of these parameters would have been better as: 238.78V, 97.08%, 676VAr and 8.53%, respectively. It was conclusive that using this module will demonstrate to students the adverse effect which poor load power factors have on the performance of short transmission lines, thus highlighting the advantage of power factor correction. It was also clear that the module will demonstrate to students the higher generation cost involved in sending electrical power to low power-factor loads.

Keywords Short Transmission Line Module Development, Short-Circuit test, open-Circuit test, Performance Analysis

1. Introduction

The capital-intensive nature of power system laboratory equipment procurement has made many tertiary institutions lacking in electrical power system laboratory facilities. Even where they are found to be provided, they are never adequate in quantity and in variety. Thus, in such a case where an institution is lacking in transmission line trainer, a very welcome idea is to improvise with a developed transmission line module. The one involved in this work was meant to satisfy short transmission line laboratory experiments.

A short transmission line is one whose length is up to a distance of 50km but less than 80km, generally [1, 2, 3]. Its operational system voltage is comparatively low, being often less than 20kV [4, 5]; but higher voltage levels up to 69kV (and not above) are equally acceptable [6]. Thus, in Nigeria our short transmission lines are mostly of 33kV voltage rating. Usually, in power system modeling, the short transmission line is represented by impedance, precisely a series impedance (since only resistance and inductance of the line are taken into account) [7]. This is because for such distances and voltage levels as stipulated above, the line shunt admittances are negligible [8, 9, 10] and a very simple network is realized. Among the transmission line data obtainable by the use of a developed short transmission line module include the following: (i) line impedance, (ii) the A, B, C, D constants, (iii) line I^2R loss, (iv) transmission efficiency, (v) voltage regulation, (vi) transmission angle, δ, (vii) the active and reactive power delivered.

By way of the organization of this paper, the next section (i.e. Section 2) shall deal with Materials and Methods. The 3rd Section has been dedicated to Test Results, Computations and Discussion; whereas, Conclusion and Recommendations shall constitute the terminal section of this paper.

2. Materials and Methods

A. Materials:

i) Core Physical Materials:

The chief material featuring in this work was a panel inductor recovered from an obsolete mercury arc rectifier (see Fig. 1(a)). The reactance and inductance of this device were unknown and had to be determined experimentally. Providing for the resistive part of the line module, a dedicated laboratory rheostat was made available (see Fig. 1(b)) to be connected in series with the inductor. This was selected after the possible full-load current of the inductor was determined.

The need for a rheostat arose more so for the laboratory work requirement of variable module impedance by resistance adjustment.

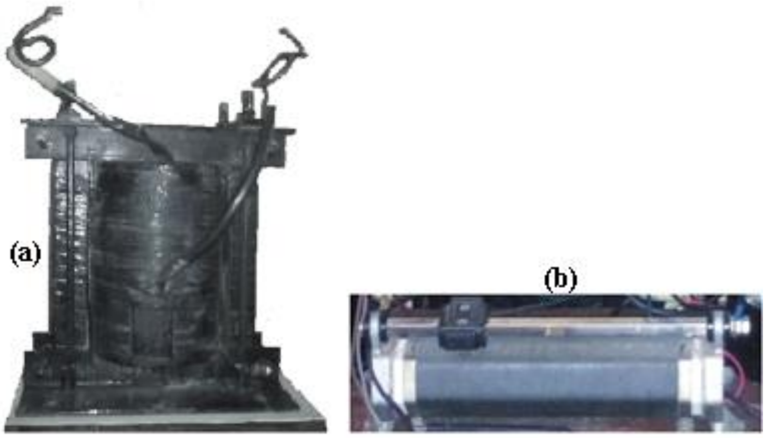

Figure 1: (a) The Recovered Panel Inductor; and (b) The Dedicated Laboratory Rheostat

ii) Equivalent Circuit and Relevant Equations:

The equivalent circuit of a short transmission line is as given in Fig. 2 (a) and the complexor or phasor diagram is provided as in Fig. 2(b) [11, 12, 13].

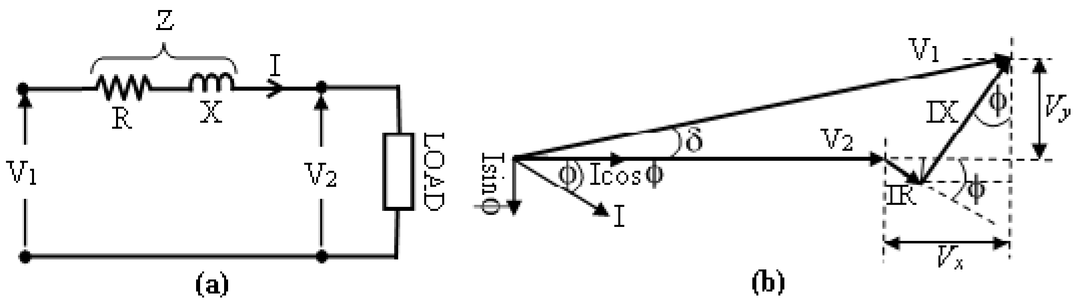

Figure 2: (a) Equivalent Circuit of a Short Transmission Line (b) Phasor Diagram of the Line.

As presented, the receiving-end voltage is made the reference vector; whilst the sending-end voltage leads it by an angle δ. The phasor diagram has been drawn in such a manner as to enable easy generation of the line equations. Definition of the circuit parameters is as follows: V_2 – Receiving End Voltage = $|V_2|/0^o$; V_1 – Sending

End Voltage = $|V_1|/\delta$; I– Line Full Load Current; R – Resistance; X – Inductive Reactance; δ – Transmission Angle; ϕ – Load Power Factor Angle; and Z = R + jX.

The relevant short-line equations as obtainable from the equivalent circuit and phasor diagram are as detailed below [13, 14, 15].

(a) Sending-End Voltage Equation: Applying Pythagora's Theorem in Fig. 3 (a) yields

$$V_1^{\,2} = (V_2 + V_x)^2 + V_y^{\,2}$$
$$= (V_2 + RI\cos\phi + XI\sin\phi)^2 + (XI\cos\phi - RI\sin\phi)^2$$
$$\therefore V_1 = \sqrt{(V_2 + RI\cos\phi + XI\sin\phi)^2 + (XI\cos\phi - RI\sin\phi)^2} \quad (1)$$

(b) Transmission Angle Equation: Equation involving the transmission angle is expressed as

$$\cos\delta = (V_2 + V_x)/V_1 = (V_2 + RI\cos\phi + XI\sin\phi)/V_1$$
$$\therefore \delta = \cos^{-1}\{(V_2 + RI\cos\phi + XI\sin\phi)/V_1\}$$
$$Or\ \ \delta = \phi' - \phi; where\ \ \phi'\ is\ the\ sending\ end\ \ power\ \ factor\ angle\ (not\ shown) \quad (2)$$

(c) Voltage Regulation Equation: The voltage regulation is given by

$$V_{reg} = (V_{2\{NO\ LOAD\}} - V_{2\{FULL\ LOAD\}})/V_{2\{FULL\ LOAD\}}$$

For short transmission line, the No-Load Receiving-End Voltage equals the Sending-End Voltage. Therefore,

$$V_{reg} = (V_1 - V_2)/V_2 \quad (3)$$

However, for very low transmission angles, which is desirable for stability purposes, the cosine of the transmission angle tends to unity and we can write

$$V_1 = V_2 + V_x = V_2 + RI\cos\phi + XI\sin\phi \quad (4)$$

Thus, an approximate voltage regulation is realized as

$$V_{reg}(approx) = (RI\cos\phi + XI\sin\phi)/V_2 \quad (5)$$

(d) Line Loss Equation: The line loss is due to the resistive parameters of the network and the equation thereof is given as

$$P_{LOSS} = I^2 R \quad (6)$$

(e) Efficiency Equation: The efficiency of any system is expressed in percentage as

$$\eta = \frac{Output\ Active\ Power, P_{OUT}}{P_{OUT} + P_{LOSS}} x100\%$$

For a short transmission line therefore we shall have

$$\eta = \frac{V_2 I\cos\phi}{V_2 I\cos\phi + I^2 R} * 100\% \quad (7)$$

Also, the relevant equations from laboratory experimental results are as provided below (involving the apparatus setup of Fig.5); where for a short transmission line the ammeters, I_1 and I_2, often register approximately the same current; hence, $I_1 = I_2 = I$.

(f) Load Power Factor and the Power Factor Angle: The load power factor and the associated power factor angle are obtained as follows

$$\cos\phi = \frac{W_2}{V_2 I} \;\; and \;\; \phi = \cos^{-1}\{W_2/(V_2 I)\} \tag{8}$$

where W_1 and W_2 are the input and output power values, respectively, as measured using wattmeters so designated.

(g) Supply Power Factor and the Power Factor Angle: Similarly, the supply power factor and the associated power factor angle are

$$\cos\phi' = \frac{W_1}{V_1 I} \;\; and \;\; \phi' = \cos^{-1}\{W_1/(V_1 I)\} \tag{9}$$

(h) Line Loss and Line Module Resistance: These are computed from the relations

$$P_{LOSS} = W_1 - W_2 \;\; and \;\; R = P_{LOSS}/I^2 \tag{10}$$

(i) Line Module Impedance, Reactance and Inductance at Rated Line Current: They are realized from

$$Z = \frac{V_1 - V_2}{I}; \;\; X = \left(Z^2 - R^2\right)^{1/2} \;\; and \;\; L = \frac{X}{2\pi f} \tag{11}$$

It is to be noted that the full-load values of the experimental data shall chiefly be used in the computations, as shall be seen shortly.

B. Methods:

In order to obtain all the short transmission line data of which the module shall be used to demonstrate to students, the methods of open-circuit test, short-circuit test and load test shall be effectively employed (see the picture of Fig. 3 for apparatus assembly).

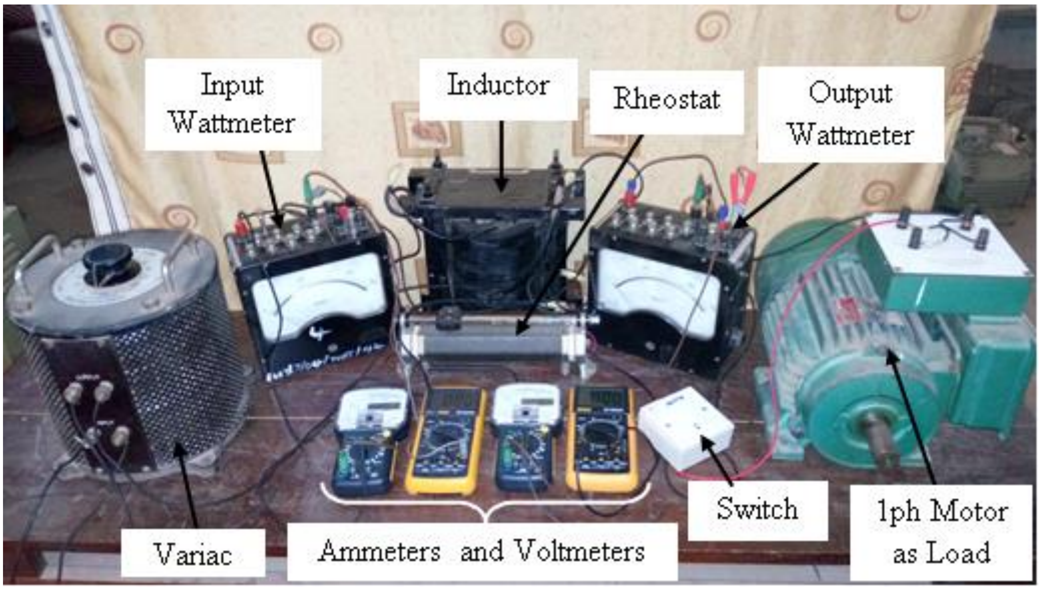

Figure 3: Apparatus as setup for Open-Circuit and Load Tests; also used as appropriate for Inductor Short-Circuit Test

i) Short-Circuit (SC) Test for Determination of Inductor Parameters:

The apparatus for this test was connected as shown in the diagram of Fig. 4. Care was taken to ascertain that the variac was initially on its zero mark. The inductor was excited until it hummed sufficiently to reflect the flow of its full-load current under short-circuit condition. The readings obtained were as follows: W = 0Watt; I = 6.22Amps; V = 89Volts.

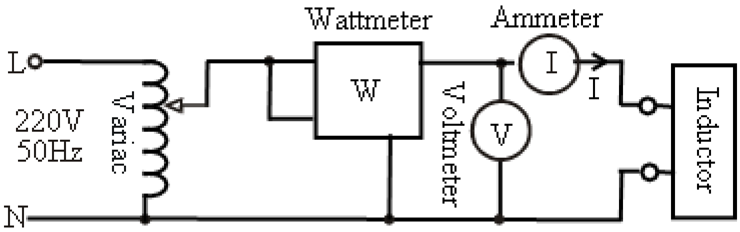

Figure 4: Apparatus as setup for Short- Circuit Test of the Inductor

ii) Selection of the Dedicated Rheostat:

Assuming the line module to deliver 6.22A at 220V to a load of standard power factor of 0.8 (lagging), we shall be dealing with a maximum output power, $P_{OUT(m)}$ = 6.22*220*0.8 = 1095W. And considering a line loss of not more than 10% of delivered active power as in [16][1], we shall be looking at a maximum line loss, $P_{LOSS(m)}$ = 1095*0.1 = 109.5W. Therefore, the total resistance of the rheostat shall not be less than, $R_{rh} = 109.5/6.22^2$ = 2.83Ω. Thus, going by the current 6.22A and resistance 2.83Ω, the available and adequate laboratory rheostat rated 4.81Ω, 10A was selected.

iii) Open-Circuit and Load (OC & L) Tests on the Line Module:

From the SC test where the input wattmeter registered zero Watt reading, it was confirmative that the recovered device was truly an inductor; hence, the need to include a resistance aspect via a rheostat, R, in the development of the short line module (see Fig. 5).

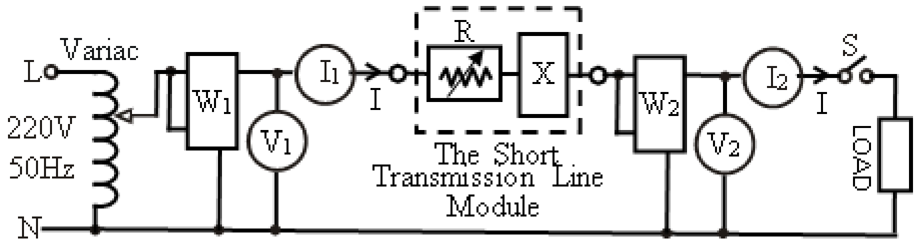

Figure 5: Apparatus as setup for Open-Circuit and Load Test of the Short Transmission Line

For the purpose of the OC & L tests of the module, the relevant equipments were connected as shown in the said figure. The OC test was carried out with the switch, S, open and voltage applied to the module by means of the variac up to the maximum possible system voltage (if not up to 220V on meter V_1). The readings on the wattmeters, ammeters and voltmeters were taken.

Then, for load test, the variac was left at the present position (of full adjustment or 220V on meter V_1, as the case may be); the rheostat was adjusted for inclusion of a small resistance and the switch was closed to supply the load. The latter was a 2.2kW, 220V, 50Hz, 14A single-phase induction motor on no-load operation. The readings on the six meters were recorded after the machine ran for a sufficient length of time. The load test was repeated, with the rheostat adjusted such that the line module power loss was not more than 10% of active power delivered.

[1] However, it is of standard generally for transmission losses to vary from 5 to 15% of total load (or receiving-end) active power [17].

3. Test Results, Computations and Discussion

A. Test Results and Computations:

The short-circuit test yielded the following W = 0Watt, I = 6.22Amps, and V = 89Volts as earlier indicated; whereas, Table 1 shows the values of active power, voltage and current obtained from the open-circuit and load tests.

Table 1: Records of the Open-Circuit and Load Tests on the Module

Test Type	W_1	W_2	V_1	V_2	A_1	A_2	Line Loss
O C Test	0.00W	0.00W	220V	205V	0.00A	0.00A	Not Applicable
L Test (1)	160W	140W	220V	161V	3.37A	3.37A	14.29%
L Test (2)	130W	120W	220V	131V	3.05A	3.05A	8.33%
Remark	*The data from load test (2) were thus used in the computations having yielded even less than 10% Line Loss.*						

The computations were carried out as detailed below.

(i) ***Output Power, Current and Power Factor on Full-Load:***

We shall consider the full exciting current of the motor as the rated full-load current of the transmission line module and this is obtainable at 220V as per the load nominal voltage rating. i.e.V_2 = 220V (on full load). Thus, the line full-load current

$$I = (220/131)*3.05 = 5.12A.$$

The output power,

$$P_{out} = (220/131)^2 *120 = 330.44W.$$

The power factor (lagging),

$$\cos\phi = \{330.44/(220*5.12)\} = 0.293; \text{ hence, } \phi = \cos^{-1}0.293 = 72.96^o.$$

The accompanying reactive power demand,

$$Q_{out} = V_2 I\sin\phi = 220*5.12*\sin 72.96^o = 1076.95 \text{ or } 1077VAr$$

ii) Total Line Loss and Resistance per-phase:

For a line loss of 8.33% of delivered power, we shall have the total line loss as,

$$P_{loss} = 0.0833*330.44 = 27.526W.$$

Thus, the line module resistance required is,

$$R = P_{loss}/I^2 = 27.526/(5.12)^2 = 1.05\Omega.$$

It is pertinent to state here that a high enough power rating of $2*P_{loss}$ = 55.052 or 55W, shall be considered should there arise a need for a discrete resistor to replace the dedicated rheostat.

iii) Input Voltage, Power, Power Factor and Transmission Angle on Full-Load:

From the original test data, the input power factor,

$$\cos\phi' = 130/(220*3.05) = 0.194; \text{ thus, } \phi' = \cos^{-1}0.194 = 78.81^o$$

The input power,

$$P_{in} = P_{out} + P_{loss} = 330.44 + 27.526 = 357.966W$$

The input voltage,

$$V_1 = \{P_{in}/(I* \cos\phi')\} = \{357.966/(5.12*0.194)\}$$
$$= 360.38 \text{ or } 360V$$

Accompanying reactive power input,

$$Q_{in} = V_1 I\sin\phi' = 360*5.12*\sin 78.81^o = 1808VAr$$

Transmission angle,

$$\delta = \phi' - \phi = 78.81^o - 72.96^o = 5.85^o$$

iv) Line Module Impedance, Reactance, Inductance and the ABCD Constants:

The line module impedance is,

$$Z = (360 - 220)/5.12 = 27.34\ \Omega; X = \{27.34^2 - 1.05^2\}^{½} = 27.32\ \Omega$$

And $L = 27.32/(2*\pi*50) = 86.96$ mH.

The impedance angle, $\theta = \tan^{-1}(27.32/1.05) = 87.8^o$

∴ B constant = $27.34/87.8^o\ \Omega$

From the OC test values, we must realize that there was no voltage drop in the line module arising from load current. The appearance of 205V on the output port instead of 220V was consequent upon the effect of a residual back voltage of 15V. However, the dimensionless parameters are,

$A = D = (V_1/V_2)_{O.C.} = (220/205) = 1.07$ (roughly unity).

And, C = 0 mho (being a short transmission line module).

v) Voltage Regulation:

Voltage regulation for short transmission line,

$V_{reg.} = \{(V_1 - V_2)/V_2\}*100 = \{(360 - 220)/220\}*100 = 63.64\%$

vi) Transmission Efficiency:

$\eta = \{P_{out}/(P_{out} + P_{loss})\}*100 = (330.44/357.966)*100 = 92.31\%$

B. Discussion:

- The impedance, Z, and the A, B, C, D constants of the line module as realized are okay as can be seen when compared with those in the referenced sources.
- From the same referenced sources, it can as well be seen that the transmission angle, δ, the transmission efficiency, η, and the transmission loss, P_{loss}, are all of acceptable standard.
- However, the extreme poverty of the load power factor, cosϕ = 0.293 (lagging), brought about very high values of input voltage, V_1, voltage regulation, V_{reg}, and reactive power quantities, Q_{in} and Q_{out}.
- Assuming the load had cosϕ = 0.8 (lagging), i.e. ϕ = 36.87°, we would have had:

$V_{reg} = (0.293/0.8)^2*63.64 = 8.537\%$ (much smaller and quite okay).

$V_1 = V_2 + (V_2*V_{reg(p.u.)}) = 220 + (220*0.08537) = 238.78V$ (smaller and okay).

$P_{out} = 220*5.12*0.8 = 915.2W$ (much larger output power for same current).

$P_{in} = 915.2 + 27.526 = 942.726W$ (much larger input power for same current).

$\cos\phi' = 942.726/(238.78*5.12) = 0.7711$ (much higher input power factor).

$\phi' = \cos^{-1}0.7711 = 39.547^o$ (smaller and better input power factor angle).

∴ $\delta = 39.547 - 36.87 = 2.677^o$ (smaller and much better transmission angle).

$\eta = (P_{out}/P_{in})*100 = (915.2/942.726)*100 = 97.08\%$ (larger and better efficiency).

$Q_{in} = 238.78*5.12*\sin 39.547^o = 778.4VAr$ (much smaller reactive power input).

$Q_{out} = 220*5.12*\sin 36.87^o = 675.8VAr$ (much smaller reactive power output).

Notice particularly, the smaller input voltage (V_1), the larger transmission efficiency (η) and the smaller voltage regulation (V_{reg}) realized with a higher load power factor. An example in [18] corroborates this analytical fact where a given power was delivered at 10kV and at 0.71 load power factor lagging; then at a higher load power factor of 0.9 (lagging) and at the same 10kV on the load end. The required input voltage, the transmission efficiency and the voltage regulation at 0.71 power factor (lagging) were 11.4kV, 96% and 14%, respectively; whereas, at 0.9 power factor (lagging) the corresponding figures were 10.8kV, 98% and 8%.

Should we therefore seize this advantage and aim at unity power factor in practice? No, because beyond 0.9 power factor lagging, unnecessary additional cost is incurred in terms of higher sizes of the compensating capacitor and cables, without appreciable differences in the values of the relevant line performance parameters.

4. Conclusion and Recommendations

A. Conclusion

It is conclusive from the analysis above that the performance of a short transmission line depends much on the load power factor (the higher the load power factor the better the transmission line performance). The short transmission line module as designed from a recovered panel inductor vis-à-vis the laboratory exercise involving the same is a good enough means of demonstrating to students the effect of load power factor on the performance of a given short transmission line. Besides the question of performance, poor load power factor increases the cost of power supply. For instance, the 360V input voltage requirement to give 220V output voltage at load power factor of 0.293 lagging, would need a step-up transformer, being beyond the range of single-phase voltages (meaning additional cost). The student can now see clearly why the improvement of power factor is of paramount significance; otherwise, the supply authority often reserves the right to surcharge industrial and commercial consumers whose loads exhibit poor power factors. However, power factor correction in practice when taken beyond 0.9 lagging can infringe considerably and unnecessarily on the engineering sense of economy.

B. Recommendations

Where a standard transmission line trainer is lacking in a power system laboratory, the development of a short transmission line module from a recovered or procured inductor and a suitable resistor (following the procedure given above) can go a long way to helping institutions meet up accreditation requirements as far as practical coverage and exercises on transmission lines are concerned. By the inclusion of suitable admittances on the input and output ports of this module, a nominal-π medium transmission line module can be realized for practical training of students. It is not mandatory that an induction motor be used as the load. A suitable laboratory inductive/resistive load bank could equally have been adopted.

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