Designing a 100kHz 32 watt Push-Pull Converter

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The push-pull converter, shown in Figure 1, is one of the oldest topologies. This topology is widely used and probably the best understood. The push-pull approach provides regulation dc isolation and conversion in one step. The push-pull converter transformer, size wise, is one of the most efficient per unit volume.

There are a multitude of converter topologies for the engineer to access and to make trade-offs on. No one converter circuit has it all. There are two outstanding drawbacks to the push-pull, center tapped converter. The action of the center tap transformer is such that each power MOSFET will see a voltage equal to twice the input voltage, plus the leakage inductance spikes. The other is flux imbalance in the power transformer. With careful design, the flux imbalance can be minimized. The push-pull transformer should not be designed with a magnetic material with a square loop, as shown in Figure 2. The normal resting point of the square loop material is at one end or the other, not in the center, also shown in Figure 2.

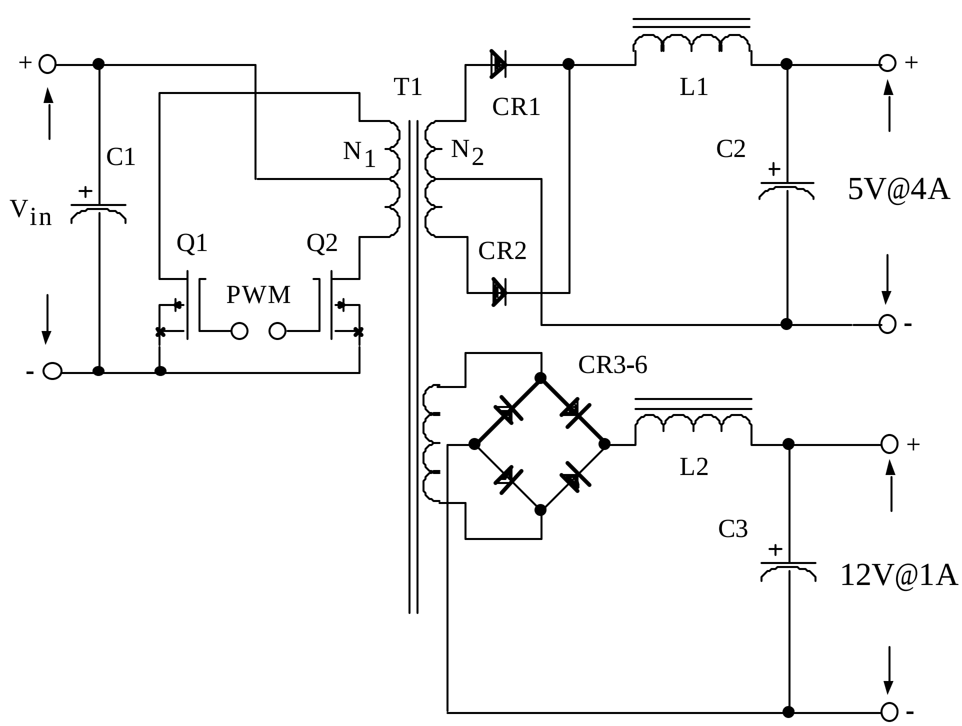

Figure 1. Push - Pull Center Tapped Converter.

The shaded area of the hysteresis is the B. The operating flux density is B/2. Ferrite material has a much more rounded hysteresis loop, as shown in Figure 3. The material shown here is Magnetics, P and R material. The lower remanence, B_r, gives a much more rounded hysteresis loop, as shown in Figure 3, and is more forgiving when there is a flux imbalance. This lower remanence, B_r, requires more driving force (H) to reach saturation.

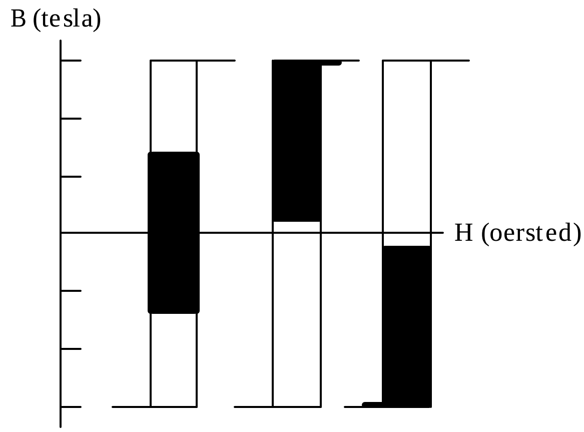

Figure 2. Typical Square Loop Magnetic Material Operating Characteristic.

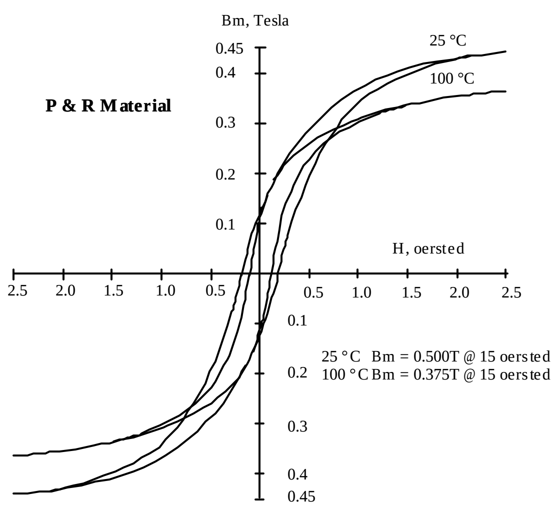

Figure 3 Typical ferrite hysteresis loop operating at 25 and 100 degrees C.

The following information is the design specification for a 38 watt push-pull transformer, operating at 100kHz, using the, K_g core geometry approach. Please refer to **Wound Magnetics Journal**, April -June 1998.

For this article, the magnetic core and wire data have been taken from the author's book, **Magnetic Core Selection for Transformers and Inductors, Second Edition.** The author will refer to chapters and page numbers in the book for a quick reference. Some of the design information has been described in past articles in the **Wound Magnetics Journal**.

For a typical design example, assume a push-pull, full wave, center tapped circuit, as shown in Figure 1, with the following specification:

1. Input voltage, $V_{in(min)} = 24$ volts
2. Output voltage, $V_o = 5$ volts @ $I_o = 4$ amps
3. Output voltage, $V_o = 12$ volts @ $I_o = 1.0$ amps
4. Frequency, f = 100,000 hertz
5. Temperature rise, 30 degrees C
6. Efficiency, $\eta = 98$ %
7. Regulation, $\alpha = 0.5$ %
8. Diode voltage drop, $V_d = 1.0$ volts
9. Design operating flux density, $B_{ac} = 0.05$ tesla
10. Notes:

    Using a center tapped winding, $P_a = 1.41$

    Using a single winding, $P_a = 1.0$

At this point, select a wire so that the relationship between the ac resistance and the dc resistance is 1:

$$\frac{R_{ac}}{R_{dc}} = 1$$

The skin depth in centimeters is:

$$e = \frac{6.62}{\sqrt{f}}, \quad [\text{cm}]$$
$$e = \frac{6.62}{\sqrt{100{,}000}}, \quad [\text{cm}]$$
$$e = 0.0209, \quad [\text{cm}]$$

Then, the wire diameter is:

$$\text{Wire Diameter} = 2(e), \quad [\text{cm}]$$
$$\text{Wire Diameter} = 2(0.0209), \quad [\text{cm}]$$
$$\text{Wire Diameter} = 0.0418, \quad [\text{cm}]$$

Then, the bare wire area A_w is:

$$A_w = \frac{p\,D^2}{4}, \quad [\text{cm}^2]$$
$$A_w = \frac{(3.1416)(0.0418)^2}{4}, \quad [\text{cm}^2]$$
$$A_w = 0.00137, \quad [\text{cm}^2]$$

From the Wire Table, in Chapter 5 on Page 187, number 27 has a bare wire area of 0.001021 centimeters. This will be the minimum wire size used in this design. If the design requires more wire area to meet the specification, then, the design will use a multifilar of #26. Listed Below are #27 and #28, just in case #26 requires too much rounding off.

Wire AWG	Bare Area	Area Ins.	Bare/Ins.	μ /cm
#26	0.001280	0.001603	0.798	1345
#27	0.001021	0.001313	0.778	1687
#28	0.0008046	0.0010515	0.765	2142

Step No. 1. Calculate the transformer output power, P_o.

$$
\begin{aligned}
P_o &= P_{o1} + P_{o2}, \quad \text{[watts]} \\
P_{o1} &= I_{o1}\left(V_{o1} + V_d\right), \quad \text{[watts]} \\
P_{o1} &= 4\left(5+1\right), \quad \text{[watts]} \\
P_{o1} &= 24, \quad \text{[watts]} \\
P_{o2} &= I_{o2}\left(V_{o2} + V_d\right), \quad \text{[watts]} \\
P_{o2} &= 1\left(12+2\right), \quad \text{[watts]} \\
P_{o2} &= 14, \quad \text{[watts]} \\
P_o &= \left(24+14\right), \quad \text{[watts]} \\
P_o &= 38, \quad \text{[watts]}
\end{aligned}
$$

Step No. 2. Calculate the secondary apparent power, P_{ts}.

$$
\begin{aligned}
P_{ts} &= P_{tso1} + P_{tso2}, \quad \text{[watts]} \\
P_{tso1} &= P_{o1}\left(P_a\right), \quad \text{[watts]} \\
P_{tso1} &= 24\left(1.41\right), \quad \text{[watts]} \\
P_{tso1} &= 33.8, \quad \text{[watts]} \\
P_{tso2} &= P_{tso2}\left(P_a\right), \quad \text{[watts]} \\
P_{tso2} &= 14\left(1\right), \quad \text{[watts]} \\
P_{tso2} &= 14, \quad \text{[watts]} \\
P_{ts} &= \left(33.8+14\right), \quad \text{[watts]} \\
P_{ts} &= 47.8, \quad \text{[watts]}
\end{aligned}
$$

Step No. 3. Calculate the total apparent power, P_t.

$$P_{in} = \left(\frac{P_o}{\eta}\right), \quad \text{[watts]}$$
$$P_{tp} = P_{in} P_a, \quad \text{[watts]}$$
$$P_t = P_{tp} + P_{ts}, \quad \text{[watts]}$$
$$P_t = \left(\frac{38}{0.98}\right)(1.41) + 47.8, \quad \text{[watts]}$$
$$P_t = 1025, \quad \text{[watts]}$$

Step No. 4. Calculate the electrical conditions, K_e.

$$K_e = 0.145\left(K_f\right)^2 (f)^2 (B_m)^2 \left(10^{-4}\right)$$
$$K_f = 4.0, \quad \text{[square wave]}$$
$$K_e = 0.145(4.0)^2 (100{,}000)^2 (0.05)^2 \left(10^{-4}\right)$$
$$K_e = 5800$$

Step No. 5. Calculate the core geometry, K_g.

$$K_g = \frac{P_t}{2K_e\alpha}, \quad [\text{cm}^5]$$
$$K_g = \frac{(102.5)}{2(5800)(0.5)}, \quad [\text{cm}^5]$$
$$K_g = 0.0177, \quad [\text{cm}^5]$$

When operating at high frequencies, the engineer has to review the window utilization factor, K_u. Please refer to the **<u>Wound Magnetics Journal</u>**, July - September 1998. When using a small bobbin, ferrites use the ratio of the bobbin winding area to the core window area. The area is only about 0.6. Operating at 100kHz and having to use a #26 wire, because of the skin effect, the ratio of the bare copper area to the total area is 0.78. Therefore, the overall window utilization K_u is reduced. To return the design back to the norm, the core geometry K_g is to be multiplied by 1.35, and then, the current density J is calculated, using a window utilization factor of 0.29.

$$K_g = 0.0177(1.35), \quad [\text{cm}^5]$$
$$K_g = 0.0239, \quad [\text{cm}^5]$$

Step No. 6. Select from TDK Corp., page 354, a PQ core comparable in core geometry K_g.

Core number	PQ-2020
Manufacturer	TDK
Magnetic material	PC44
Magnetic path length , MPL	4.5 cm
Window height	1.43 cm
Core weight, W_{tfe}	15 grams
Copper weight, W_{tcu}	10.2 grams
Mean length turn, MLT	4.4 cm
Iron area, A_c	0.62 cm^2
Window area, W_a	0.658 cm^2
Area product, A_p	0.408 cm^4
Core geometry, K_g	0.0232 cm^5
Surface area, A_t	19.7 cm^2
Millihenrys per 1000 turns, AL	3150

Step No. 7. Calculate the number of primary turns, N_p, using Faradays Law.

$$N_p = \frac{V_p\left(10^4\right)}{K_f\ B_{ac}\ f A_c}, \quad \text{[turns]}$$

$$N_p = \frac{(24)\left(10^4\right)}{(4.0)(0.05)(100000)(0.62)}, \quad \text{[turns]}$$

$$N_p = 19, \quad \text{[turns]}$$

Step No. 8. Calculate the current density J using a window utilization, $K_u = 0.29$.

$$J = \frac{P_t\left(10^4\right)}{K_f\ K_u\ B_{ac}\ f A_p}, \quad [\text{amps/cm}^2]$$

$$J = \frac{(102.5)\left(10^4\right)}{(4.0)(0.29)(0.05)(100000)(0.408)}, \quad [\text{amps/cm}^2]$$

$$J = 433, \quad [\text{amps/cm}^2]$$

Step No. 9. Calculate the input current, I_{in}.

$$I_{in} = \frac{P_o}{V_{in}\eta}, \quad \text{[amps]}$$

$$I_{in} = \frac{38}{(24)(0.98)}, \quad \text{[amps]}$$

$$I_{in} = 1.61, \quad \text{[amps]}$$

Step No. 10. Calculate the primary bare wire area, $A_{wp(B)}$.

$$A_{wp(B)} = \frac{I_{in}\sqrt{D_{\max}}}{J}, \quad [\text{cm}^2]$$

$$A_{wp(B)} = \frac{(1.61)\sqrt{0.5}}{433}, \quad [\text{cm}^2]$$

$$A_{wp(B)} = 0.00263, \quad [\text{cm}^2]$$

Step No. 11. Calculate the required number of primary strands, S_{np}.

$$S_{np} = \frac{A_{wp(B)}}{\#26}$$

$$S_{np} = \frac{0.00263}{0.00128}$$

$$S_{np} = 2.05, \quad \text{[use 2]}$$

Step No. 12. Calculate the primary new µ per centimeter.

$$(\text{new})\frac{m\Omega}{\text{cm}} = \frac{\frac{m\Omega}{\text{cm}}}{S_{np}}$$

$$(\text{new})\frac{m\Omega}{\text{cm}} = \frac{1345}{2}$$

$$(\text{new})\frac{m\Omega}{\text{cm}} = 673$$

Step No. 13. Calculate the primary resistance, R_p.

$$R_p = \text{MLT}(N_p)\left(\frac{m\Omega}{\text{cm}}\right)(10^{-6}), \quad \text{[ohms]}$$

$$R_p = (4.4)(19)(673)(10^{-6}), \quad \text{[ohms]}$$

$$R_p = 0.0563, \quad \text{[ohms]}$$

Step No. 14. Calculate the primary copper loss, P_p.

$$P_p = I_p^2 R_p, \quad [\text{watts}]$$
$$P_p = (1.61)^2 (0.0563), \quad [\text{watts}]$$
$$P_p = 0.146, \quad [\text{watts}]$$

Step No. 15. Calculate the secondary turns, N_{s1}.

$$N_{s1} = \frac{N_p V_{s1}}{V_{in}}\left(1 + \frac{a}{100}\right), \quad [\text{turns}]$$
$$V_{s1} = V_o + V_d, \quad [\text{volts}]$$
$$V_{s1} = 5 + 1, \quad [\text{volts}]$$
$$V_{s1} = 6, \quad [\text{volts}]$$
$$N_{s1} = \frac{(19)(6)}{(24)}\left(1 + \frac{0.5}{100}\right), \quad [\text{turns}]$$
$$N_{s1} = 4.77 \text{ use } 5, \quad [\text{turns}]$$

Step No. 16. Calculate the secondary turns, N_{s2}.

$$N_{s2} = \frac{N_p V_{s2}}{V_{in}}\left(1 + \frac{a}{100}\right), \quad [\text{turns}]$$
$$V_{s2} = V_o + 2V_d, \quad [\text{volts}]$$
$$V_{s2} = 12 + 2, \quad [\text{volts}]$$
$$V_{s2} = 14, \quad [\text{volts}]$$
$$N_{s2} = \frac{(19)(14)}{(24)}\left(1 + \frac{0.5}{100}\right), \quad [\text{turns}]$$
$$N_{s2} = 11.1 \text{ use } 11, \quad [\text{turns}]$$

Step No. 17. Calculate the secondary bare wire area, A_{ws1}.

$$A_{ws1(B)} = \frac{I_{o1}\sqrt{D_{max}}}{J}, \quad [\text{cm}^2]$$
$$A_{ws1(B)} = \frac{(4)\sqrt{0.5}}{433}, \quad [\text{cm}^2]$$
$$A_{ws1(B)} = 0.00653, \quad [\text{cm}^2]$$

Step No. 18. Calculate the required number of secondary strands, S_{ns1}.

$$S_{ns1} = \frac{A_{ws1(B)}}{\#26}$$
$$S_{ns1} = \frac{0.00653}{0.00128}$$
$$S_{ns1} = 5.1, \quad [\text{use } 5]$$

Step No. 19. Calculate the secondary, S_1 new µ per centimeter.

$$(\text{new})\frac{m\Omega}{\text{cm}}=\frac{\frac{m\Omega}{\text{cm}}}{S_{ns1}}$$
$$(\text{new})\frac{m\Omega}{\text{cm}}=\frac{1345}{5}$$
$$(\text{new})\frac{m\Omega}{\text{cm}}=269$$

Step No. 20. Calculate the secondary S_1 resistance, R_{s1}.

$$R_{s1}=\text{MLT}(N_{s1})\left(\frac{m\Omega}{\text{cm}}\right)\left(10^{-6}\right),\quad [\text{ohms}]$$
$$R_{s1}=(4.4)(5)(369)\left(10^{-6}\right),\quad [\text{ohms}]$$
$$R_{s1}=0.0059,\quad [\text{ohms}]$$

Step No. 21. Calculate the secondary copper loss, P_{s1}.

$$P_{s1}=I_{s1}^2R_{s1},\quad [\text{watts}]$$
$$P_{s1}=(4.0)^2(0.0059),\quad [\text{watts}]$$
$$P_{s1}=0.0944,\quad [\text{watts}]$$

Step No. 22. Calculate the secondary bare wire area, $A_{ws1(B)}$.

$$A_{ws2(B)}=\frac{I_{o2}}{J},\quad [\text{cm}^2]$$
$$A_{ws2(B)}=\frac{(1)}{433},\quad [\text{cm}^2]$$
$$A_{ws2(B)}=0.00231,\quad [\text{cm}^2]$$

Step No. 23. Calculate the required number of secondary strands, S_{ns2}.

$$S_{ns2}=\frac{A_{ws2(B)}}{\#26}$$
$$S_{ns2}=\frac{0.00231}{0.00128}$$
$$S_{ns2}=1.8,\quad [\text{use } 2]$$

Step No. 24. Calculate the secondary, S_2 new μ per centimeter.

$$(\text{new})\frac{m\Omega}{\text{cm}}=\frac{\frac{m\Omega}{\text{cm}}}{\text{S}_{\text{ns1}}}$$

$$(\text{new})\frac{m\Omega}{\text{cm}}=\frac{1345}{2}$$

$$(\text{new})\frac{m\Omega}{\text{cm}}=673$$

Step No. 25. Calculate the secondary, S_2 resistance, R_{s2}.

$$R_{s2}=\text{MLT}\left(N_{s2}\right)\left(\frac{m\Omega}{\text{cm}}\right)\left(10^{-6}\right),\quad [\text{ohms}]$$

$$R_{s2}=(4.4)(11)(673)\left(10^{-6}\right),\quad [\text{ohms}]$$

$$R_{s2}=0.0326,\quad [\text{ohms}]$$

Step No. 26. Calculate the secondary, S_2 copper loss, P_{s2}.

$$P_{s2}=I_{s2}^2 R_{s2},\quad [\text{watts}]$$

$$P_{s2}=(1.0)^2(0.0326),\quad [\text{watts}]$$

$$P_{s2}=0.0326,\quad [\text{watts}]$$

Step No. 27. Calculate the total secondary copper loss, P_s.

$$P_s=P_{s1}+P_{s2},\quad [\text{watts}]$$

$$P_s=0.0944+0.0326,\quad [\text{watts}]$$

$$P_s=0.127,\quad [\text{watts}]$$

Step No. 28. Calculate the total primary and secondary copper loss, P_{cu}.

$$P_{cu}=P_p+P_s,\quad [\text{watts}]$$

$$P_{cu}=0.146+0.127,\quad [\text{watts}]$$

$$P_{cu}=0.273,\quad [\text{watts}]$$

Step No. 29. Calculate the transformer regulation, α.

$$a=\frac{P_{cu}}{P_o}(100),\quad [\%]$$

$$a=\frac{(0.273)}{(38)}(100),\quad [\%]$$

$$a=0.718,\quad [\%]$$

Step No. 30. Calculate the milliwatts per gram, mW/g.

$$\frac{mW}{gram} = 0.000318\,(f)^{(1.51)}\,(B_{ac})^{(2.747)}$$
$$\frac{mW}{gram} = 0.000318\,(100000)^{(1.51)}\,(0.05)^{(2.747)}$$
$$\frac{mW}{gram} = 3.01$$

Step No. 31. Calculate the core loss, P_{fe}.

$$P_{fe} = \left(\frac{mW}{gram}\right)(W_{tfe})(10^{-3}), \quad \text{[watts]}$$
$$P_{fe} = (3.01)(15)(10^{-3}), \quad \text{[watts]}$$
$$P_{fe} = 0.045, \quad \text{[watts]}$$

Step No. 32. Calculate the total loss, P_{Σ}.

$$P_{\Sigma} = P_{cu} + P_{fe}, \quad \text{[watts]}$$
$$P_{\Sigma} = (0.273) + (0.045), \quad \text{[watts]}$$
$$P_{\Sigma} = 0.318, \quad \text{[watts]}$$

Step No. 33. Calculate the watts per unit area, ψ.

$$y = \frac{P_{\Sigma}}{A_t}, \quad \text{[watts per cm}^2\text{]}$$
$$y = \frac{(0.318)}{(19.7)}, \quad \text{[watts per cm}^2\text{]}$$
$$y = 0.0161, \quad \text{[watts per cm}^2\text{]}$$

Step No. 34. Calculate the temperature rise, T_r.

$$T_r = 450\,(y)^{(0.826)}, \quad [\,^{o}C]$$
$$T_r = 450\,(0.0161)^{(0.826)}, \quad [\,^{o}C]$$
$$T_r = 14.9, \quad [\,^{o}C]$$

Step No. 35. Calculate the total window utilization, K_u.

$$K_u = K_{up} + K_{us}$$
$$K_{us} = K_{us1} + K_{us2}$$
$$K_{us1} = \frac{N_{s1} S_{n1} A_{ws1}}{W_a}$$
$$K_{us1} = \frac{(10)(5.0)(0.001603)}{(0.658)} = 0.122$$
$$K_{us2} = \frac{(11)(2.0)(0.001603)}{(0.658)} = 0.0536$$
$$K_{up} = \frac{N_p S_{np} A_{wp}}{W_a}$$
$$K_{up} = \frac{(38)(2.0)(0.001603)}{(0.658)} = 0.184$$
$$K_u = (0.185) + (0.122 + 0.0536)$$
$$K_u = 0.361$$

Summary:

The above transformer was built, and tested. It meets the intent of the specification. The copper and core loss could be brought more in line (could be equal) by increasing the flux density. This increase would have made a more efficient transformer, but would have an impact on the volts per turn, which is, again, another tradeoff. The author hopes that this article with its
step by step approach helps the readers understand the design of a push-pull converter transformer.

The Author would like to thank Sherwood Associates for providing the TDK core, and Shafer Magnetic Components for building the transformer to prove form, fit and function. I would like to thank Bob Yahiro who has been reviewing the math in all of my articles.

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The information in the book, ***Magnetic Core Selection for Transformers and Inductors ,.Second Edition*** , is an invaluable reference enabling engineers to quickly compare components and select the one best-suited to their needs in a minimum amount of time.

The author is now serving as a consultant for the Reliability Engineering Office at the Jet Propulsion Laboratory, in Pasadena, California. He is working on reliability and robust issues for Wound Magnetics design.

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Software
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