TOSHIBA

APPLICATION NOTE
M-2

Magnetic Amplifier Regulation of Switch Mode Power Supplies

Basic Design of Saturable Reactors

A Magnetic Amplifier (or "Mag-Amp") is a post regulation method utilizing a saturable reactor (wire-wrapped saturable core). It regulates the auxiliary outputs of a switching power supply by delaying the rise in voltage of a PWM pulse. In this note, the basic design of a Mag-Amp will be discussed.

The transformer secondary voltage should allow, after Pulse Width Modulation, for an additional 20% (i.e. "headroom") over the desired main output voltage:

$$V_S \cdot (T_{ON} / T) = 1.2 \cdot V_1 \quad (1)$$

where:

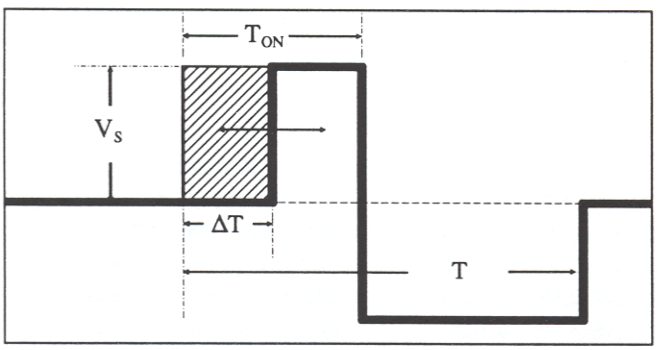
V_S = Transformer Secondary Voltage
V_1 = Main Output Voltage

For the auxiliary output, the Mag-Amp delays the rise in the voltage pulse by an amount ΔT. Hence the auxiliary output voltage, V_2, plus headroom is given by:

$$V_S \cdot ((T_{ON} - \Delta T) / T) = 1.2 \cdot V_2 \quad (2)$$

where:

V_2 = Auxiliary Output Voltage
ΔT = Delay time (see the figure below)



The magnetic flux blocked by the Mag-Amp, Φ, is the shaded area above:

$$\Phi = V_S \cdot \Delta T \quad [\text{Wb}] \quad (3a)$$

Substituting Equations (1) and (2) into Equation (3a):

$$\Phi = 1.2 \cdot (V_1 - V_2) / f \quad (3b)$$

where:

f = Switching Frequency = 1 / T

For the Mag-Amp to regulate the circuit, the magnetic flux of the Mag-Amp must be at least that obtained in Equation 3:

$$N \cdot \Phi_C \geq \Phi \quad (4)$$

where:

N = Number of turns of wire
Φ_C = Flux in Saturable Core

Another necessary requirement for a Mag-Amp is that the area available in the core for wire winding be at least the area of the required windings:

$$A_W \cdot K_W \geq N \cdot A_{Wire} \quad (5)$$

where:

A_W = Core winding area [mm²]
K_W = Winding factor (typical value = 0.4)
A_{Wire} = Cross-Sectional area of the wire [mm²]

The following is obtained from Conditions 4 & 5:

$$\Phi_C \cdot A_W \geq \Phi \cdot I_S / (K_W \cdot J) \quad [\text{Wb·mm}^2] \quad (6)$$

where:

I_S = Auxiliary Output Current
J = Average Current Density [A/mm²]

The appropriate core is selected by calculating the Right Hand side of Condition 6 and comparing the result to the values of $\Phi_C \cdot A_W$ for saturable cores. Usually the smallest core fulfilling Condition 6 is selected. Table 1 (on the reverse side) lists these values for Toshiba's MS Series of Amorphous Magnetic Saturable Cores.

Once a core is selected, the number of turns, N, in the winding for the saturable reactor can be obtained by rearranging Condition 4:

$$N \geq \Phi / \Phi_C \quad [\text{turns}] \quad (7)$$

where:

Φ_C = Magnetic flux of the core selected.

The diameter of the winding wire, d, is:

$$d \geq 2 \cdot (I_S / \{\pi \cdot J\})^{0.5} \quad [\text{mm}] \quad (8)$$

Conditions 6 - 8 determine the basic design of a Mag-Amp. However, specific circuit conditions may indictate other selections be used.

EXAMPLE

Design a Mag-Amp to regulate an auxiliary output voltage of 5V and output current of 4A. The main output voltage is 12V and the switching frequency is 200kHz.

For an auxiliary output voltage V_2 = 5V; a main output voltage V_1 = 12 V; and frequency f = 200 kHz; the required magnetic flux, from Equation (3b), for regulation should be:

$$\Phi = 1.2 \times (12V - 5V) / (200{,}000\,Hz) = 42\,\mu Wb$$

For an output current I_S = 4A; assuming an average current density of J = 5 A/mm²; Condition 6 leads to:

$$\Phi_C \cdot A_w > 42 \times 10^{-6}\,Wb \times 4A \,/\, (0.4 \times 5A/mm^2)$$
$$> 84\ \mu Wb{\cdot}mm^2$$

Therefore, from Table 1, Toshiba Amorphous Saturable Core MS 10x7x4.5W is selected.

From Table 1, the total magnetic flux, Φ_C, of an MS 10x7x4.5W core is 4.73 µWb. From Condition 7 the number turns of the coil, N, of the saturable reactor is obtained:

$$N \geq 42 \times 10^{-6}Wb \,/\, (4.73 \times 10^{-6}Wb) = 8.9$$
$$\therefore\ N = 9 \text{ turns}$$

The winding wire diameter, d, is determined from Condition 8:

$$d \geq 2 \times (4/\{\pi \times 5\})^{0.5} = 1.00\,mm$$
$$\therefore\ d = 1\,mm \text{ is selected}$$

To regulate this output, use an MS 10x7x4.5W core with 9 turns of 1 mm wire.

Table 1
Toshiba Amorphous Saturable Cores - MS Series

Part Number	Core Size O.D. [mm]	I.D. [mm]	Height [mm]	Cross-Sectional Area [mm²]	Magnetic Path Length [mm]	Total Flux [µWb]	$\Phi_c \cdot A_W$ [µWb·mm²]
MS 7x4x3W	7.5	4.5	3	3.38	18.8	3.16	21
MS 8x7x4.5W	8	7	4.5	1.69	23.6	1.58	36
MS 9x7x4.5W	9	7	4.5	3.38	25.1	3.16	72
MS 10x7x4.5W	10	7	4.5	5.06	26.7	4.73	96
MS 10x6x4.5W	10	6	4.5	6.75	25.1	6.31	108
MS 12x8x3W	12	8	3	4.50	31.4	4.20	119
MS 12x8x4.5W	12	8	4.5	6.75	31.4	6.31	197
MS 14x8x4.5W	14	8	4.5	10.13	34.6	9.47	295
MS 15x10x3W	15	10	3	5.63	39.3	5.26	264
MS 15x10x4.5W	15	10	4.5	8.44	39.3	7.89	427
MS 18x12x4.5W	18	12	4.5	10.13	47.1	9.47	774
MS 21x14x4.5W	21	14	4.5	11.81	55.0	11.04	1249

Table 2 is provided as an approximate guide to select a Mag-Amp. It is intended to be used **ONLY as Guide.**

Table 2
Mag-Amp Selection Guide (200 kHz)

Forward Converter		OUTPUT CURRENT 2 Amps	4 Amps	8 Amps
Output	**1 V**	MS 8x7x4.5W - 4 Turns	MS 8x7x4.5W - 4 Turns	MS 8x7x4.5W - 4 Turns
Voltages	**3 V**	MS 8x7x4.5W - 11 Turns	MS 9x7x4.5W - 6 Turns	MS 10x7x4.5W - 4 Turns
Difference	**5 V**	MS 8x7x4.5W - 19 Turns	MS 9x7x4.5W - 9 Turns	MS 12x8x4.5W - 5 Turns
($V_1 - V_2$)	**7 V**	MS 9x7x4.5W - 13 Turns	MS 10x7x4.5W - 9 Turns	MS 12x8x4.5W - 7 Turns
	9 V	MS 9x7x4.5W - 17 Turns	MS 12x8x4.5W - 9 Turns	MS 15x10x4.5W - 7 Turns

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