Circuit and Electromagnetic System Design Notes

Note 16

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x = Major Items

MARX-LIKE GENERATORS AND CIRCUITS

Brief review of some modern Marx generators.
x Untriggered gap Marx generators.
x Trigger gap Marx generators.
x Triggering range: the need for a reasonably wide triggering range.
Erection time and the jitter of this.
Inductance of Marx generators.
High voltage gradient Marx generators.
Peaking capacitor circuits for decreased rise time.
x Cheap one million volt, low inductance condensers.
L/R Marx output circuit.

EXTRA TOPICS NOT INCLUDED

LECTURE NO. 3

MARX GENERATORS

Two useful versions of Marx generators will be briefly described in these notes, untriggered and triggered.

The untriggered Marx works by overvolting the higher gaps by linking an impedance across a number of gaps (n). All impedances directly across one gap tend to prevent the voltage on the gap rising and hence inhibit triggering. However if these impedances are counteracted by ones across more than one gap this aids triggering. Figure 1 shows a schematic with impedances linked across every third gap, a $n = 3$ case. The parameter n of course can have any number greater than one and when the higher order impedances swamp the $n = 1$ impedances a total of nV appears across the gaps. A minimum of $n - 1$ gaps have to be triggered at the base of the Marx to start the propagating erection wave. If capacity coupling is used, the needed linking capacities can be built in as strays up the Marx, but then it is not usually possible to make these greatly bigger than those across the individual gaps and less than nV appears across the n^{th} gap up, after the ones below have fired. However this voltage will appear quickly, the rise time of the triggering pulse being determined by the breakdown time of a gap, and the inductance and capacity of the circuit involved in feeding the pulse up.

If resistive coupling is used this will provide the full nV after a time characterised by the discharge time of the gap strays via the multistage linking resistors. Thus the mode tends to have the largest triggering range but a slightly slower erection. In a Marx built of small value capacitors, this mode of coupling may not be of use, as the lower stages of the Marx may discharge while the erection is taking place.

The two modes can be combined and figure 2 shows an example of a $n = 3$, R and C-coupled Marx.

The minimum number of charging resistor chains needed is $n + 1$, where one high impedance chain links across all the gaps and n much lower impedance chains link each across n gaps. However if helpful stray capacities are built into the Marx, by stacking it in n columns of capacitors, it is frequently more convenient to use 2n charging chains, especially if plus and minimum charging is being employed.

A $n = 2$ Marx will have a triggering range down to about 60% of self break voltage, provided the set of gaps in the Marx has a low standard deviation of breakdown, and gets UV irradiation from the lower gaps. However, in general $n = 3$ is the best number for a reasonably wide range Marx, a good version of which will trigger down to about 40% of self break.

The triggered Marx obviously has the added complication of a third electrode in each gap, but has three significant advantages which may more than justify this. Firstly it can operate with arbitrarily large capacities across each gap. Such capacities are an essential consequence of building low inductance Marx generators because of the strip line feeds from the gaps to the capacitors. Secondly, the gaps can be in separate bodies without paying a penalty in triggering range as UV irradiation between gaps is unnecessary. Thirdly, much smaller transient voltages can be made to appear across each gap during the erection and this can considerably ease internal flashover problems in high gradient generators.

Figure 3 shows a schematic for a triggered Marx with impedances across three gaps (m = 3). This provides a total voltage excursion of 3V on the trigger electrode when the added impedances swamp the strays. However the voltage applied to the second part of the gap after the first part has fired, will not be much bigger than V unless steps are taken to ensure this. Figure 4 shows a schematic of an m = 3 Marx with added resistive coupling. In this case plus and minus charging is employed using high impedance chains and the m coupling is obtained by use of 3 earth resistance chains attached to the midpoint of the two capacitors in each stage.

For very low inductances Marx generators with big strays across each gap, this technique may not be of too much use as it may take too long to operate, but better operation can still be obtained by off-setting the trigger electrode so the gaps tend towards "simultaneous" operation. Considerable expertise is required to make the Marx operate in this mode; however it is considered to be the best one to achieve multichannel operation with and offers the lowest possible inductance in a single Marx. Such a system was designed at AWRE in 1969 but has not been built and operated to date.

Reference 1 gives details of an n = 2, RC coupled Marx, while reference 2 covers the case of an m = 2, C coupled Marx.

In general a very good range of operation can be obtained with an m = 2 triggered Marx providing this is not of the very lowest inductance type, and triggering down to 30% of self break can be obtained with R coupling added. For the lowest inductance systems m = 3 with offset triggers appear to be necessary.

ERECTION TIME

Both of the above notes give the erection time for the particular Marxes and show that (a) fast erection times can be easily obtained and (b) there are wide ranges of operating conditions where these do not change significantly.

Physics International on one occasion built several Marx generators of the same design, each being a large energy system with m = 3 and containing 20 stages with an output voltage of 2MV. The erection time for a given Marx was about 210 ns with a shot to shot jitter of $\pm$ 3 ns and a set of four of the Marx systems had mean erection times within a span of 15 ns under the same set of gap pressures etc.

The erection time can be calculated roughly. Firstly the collapse time of the voltage across a gap is calculated, then the integration effects of the feed up the trigger resistors is calculated. A guess at the equally spaced time of operation of the preceding m - 1 gaps is made and the resulting trigger waveform on the m th gap in the set is obtained; the edge plane streamer relation is used to obtain the firing time of the first part of the gap, and then that of the second. These times are used to check that the total time to fire the set of m gaps is consistent with the value assumed earlier in the calculation. This total firing gap time is divided by m to give the effective single gap time, on the assumption of a stable propagating erection phase moving up an infinitely long Marx. However real Marx generators have a finite number of stages and as the wave propagates up the Marx, the voltage on the higher gaps increases. The way this happens depends on whether the output of the Marx is effectively earthed (as in a peaking capacitor case) or is pseudo unearthed (only having its stray capacity to earth ground it) thus the erection process speeds up as it proceeds and may indeed start from the top and fire downwards in some cases towards the end of the erection phase. Thus the erection time is not the above single gap firing time multiplied by the number of stages in the Marx, but something smaller. For earthed Marxes a fudge that is usually good is to multiply by 0.4 of the number of stages, while for a pseudo open circuit case a factor of 0.7 is frequently applicable.

In general the resulting erection times so calculated are in agreement with the observed times to a factor of 1 1/2 or so and have a pressure dependency similar to the observed one. Their real value is in deciding what changes can be usefully made to the many circuit parameters in order to speed up the process and which changes are unlikely to be worthwhile. Of course the first m - 1 gaps have to be properly fired, and that this is the case should be checked by monitoring the time of closure of these gaps in a separate experiment.

MARX INDUCTANCE

This can be crudely calculated using the methods outlined in NPT notes to obtain the inductance of each bit of the circuit; an example is given in reference 2. Again the real value of such calculations, apart from deriving an approximate value of the inductance of the system before it is built, is that if the inductance of some portion of the system is an unduly large fraction of the total system inductance, steps may be taken to reduce this and so make a worthwhile improvement. If the system has several bits, all of which have roughly the same inductance, improving one will have little effect. Equally if one is increased by a factor of 2 for high voltage or mechanical assembly reasons, it will have little effect on the overall inductance. In such a balanced set up, if an improved inductance is needed a completely new approach is usually necessary, such as a change from untriggered to triggered systems. Of course the overall inductance is not just the sum of the component capacitors, feeds, and spark gaps but also involves the inductance viewed as a conductor rising the height of the Marx as well as that of the output feeds joining it to the lead.

PEAKING CAPACITORS

This topic is dealt with in reference 2 and will not be further covered here as is the topic of cheap high voltage pulse charged low inductance capacitors, except to point out that as the peaking capacitor becomes comparable in value to the Marx capacitor it becomes what is called a transfer capacitor. This is simply a pulse charged high voltage capacitor of superior performance, to which the energy of the Marx is transferred so that it can be more quickly applied to the load. As such most of the systems mentioned in the fourth lecture can be described rather inadequately as transfer capacity systems.

L/R MARX OUTPUT CIRCUIT

In some cases the essentially exponential tail of the output waveform of Marx feeding a constant resistance load is undesirable. This is the case for some e beam generators where a few microsecond roughly flat top waveforms can be desirable. There are a number of approaches to this, the first is to use a Marx with a large output capacity but this is wasteful of energy. Another approach is to build a lumped constant delay line out of high voltage components. However a third rather crude approach is to put an inductance L bypassed by a resistance R in the output of the Marx. Figure 5 gives the circuit.

Initially the resistance R is in series with the constant load resistance Z but as the voltage of the Marx (viewed as a lumped circuit capacitor) falls, the current transfers to the inductance. The circuit can be arranged so that the voltage across Z rises after the switch-on front, peaks and then falls back to the same value at the end of the phase under consideration. Thus an output pulse across Z has a variation of say $\pm$ 5% or $\pm$ 10% up to some time at which the voltage begins to decay fairly rapidly in a roughly exponential fashion. If a dump or divertor gap is then fired, an approximately flat top pulse is obtained. The energy transfer to the load can be quite large (> 50%) at the expense of having an output voltage of about 3/4 of the open circuit value of the Marx. Figure 5 gives the results of some calculations made a couple of years ago for the circuit and uses the optimum values for L and R. The calculated values have not been checked by myself since doing them but are within a few per cent of the correct ones.

The inductor and resistor are very simple components to make from a high voltage point of view and can be easily altered to cover any desired range of parameters. Probably the best way is to wind the inductance along a copper sulphate resistor when the best grading is achieved. 20 kV/cm gradients can be supported on such an arrangement in air, probably twice this in freon and of course the components can be oil immersed or, less desirably, potted.

For further details of the calculations the author could be consulted but the circuit analysis is pretty simple.

If a fast rise time to the pulse is required, (and razor blade cathodes need a fairly fast switch on pulse) a peaking capacitor can be included in between the Marx and the L/R arrangement. Some small oscillations on the output waveform would be expected to result from this combination, but if these cannot be accepted damping resistors can be used to reduce their amplitude to low levels.

AIR CORED TRANSFORMERS

The section in the NPT note describes the techniques for use in high voltage versions of these systems. However for lower voltage operation copper sulphate solution impregnation is not necessary. The air cored transformer can have either a single sided output referenced to earth or can have a plus and minus output of twice the total output. The rough guides given below to the output pulse amplitude are for the single sided output; the values have to be doubled for the other case. For voltages up to 100 kV plus the winding need not be impregnated although above 100 kV some loading due to corona in the windings is to be expected. Up to 250 kV plus transformer oil impregnation can be used, which is an advantage as it does not evaporate. Using solution resistive grading, voltages up to 2 MV can be generated in transformers a couple of cubic feet in volume. The above guides for output voltage are only rough and depend a bit on size of the transformer.

Reference 1 gives a complete calculation for a trigger transformer and the approximate relations used. These relations are summarised in figure 6 and can be used not only to calculate the open circuit gain but also that to be expected from addition resistive or capacitive loading of the transformer.

Care must be taken to keep the impedance of the capacitor driving circuit low and the relations given show how the inductance and resistance of this affect the output obtained. The relationships and expressions are only approximate and give answers to about 5% in general. However they are simple enough to allow an optimisation of a transformer to be done. In general there is a turns ratio which gives a calculated maximum output, however it is desirable to work a little below this, to keep the output impedance lower than would be the case with the calculated optimum. Also of course the high voltage tracking lengths have to be borne in mind otherwise these may get too small, and these dictate some of the dimensions. Reference 3 gives a detailed description of a $\pm$ 1 MV pulse transformer built at AWRE by Dr. Dave Hammer, however in general for this voltage range a Marx is a better bet especially if it has to transfer many kilojoules.

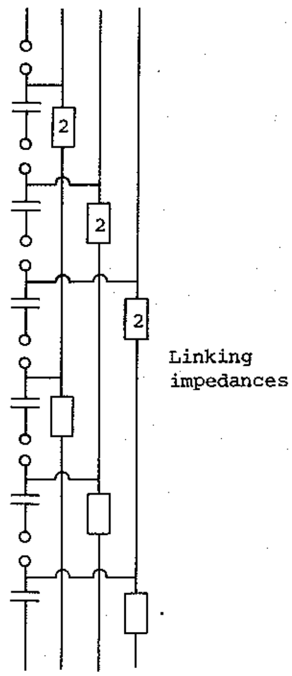
It is not necessary to go the system outlined in the above notes for many trigger applications and well insulated wire, in-intelligently wound on a few turn primary can be used to give gains of ten or so and output voltages up to 100 kV or more. However for high gains and fast rise times it is usually worth the effort to construct them as described.

REFERENCES

1. "Mini B Design and Operation" T. H. Storr, SSWA/THS/692/9.

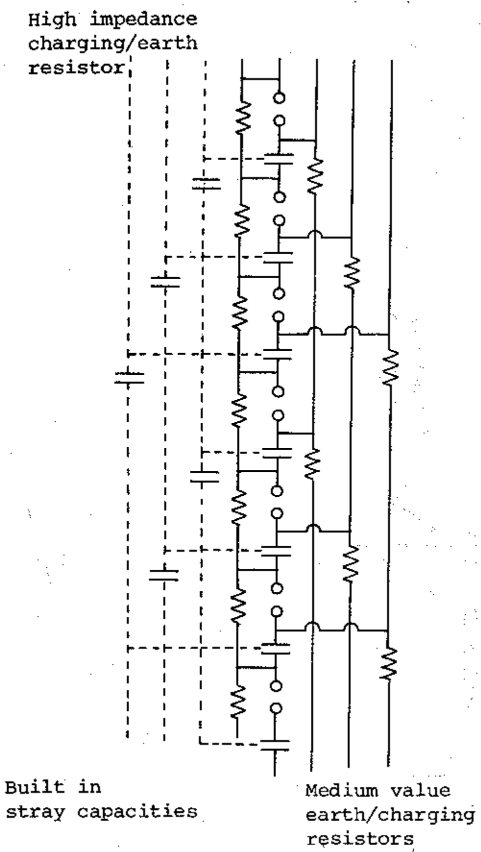
2. "Notes for a Report on the Generator TOM" J. C. Martin, SSWA/JCM/735/407.

3. "Notes on the Construction of a High Voltage Pulse Transformer" J. C. Martin, P. D. Champney, D. A. Hammer, Cornell University CU-NRL/2.



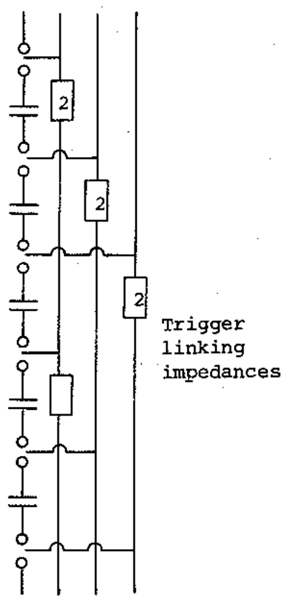
Untriggered Marx n = 3

FIGURE 1



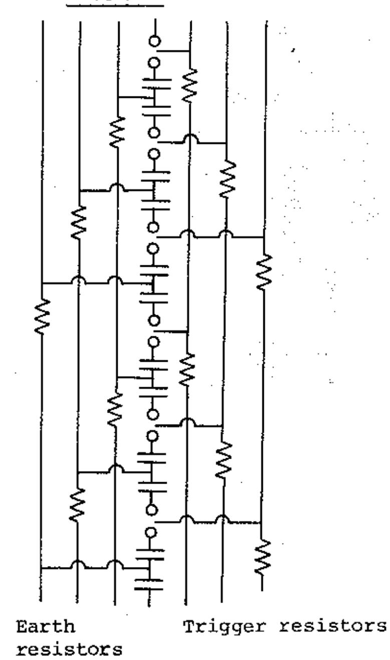
n = 3 R,C coupled

FIGURE 2



Triggered Marx m = 3

FIGURE 3



High impedance
charging chains omitted

m = 3 R coupled

FIGURE 4

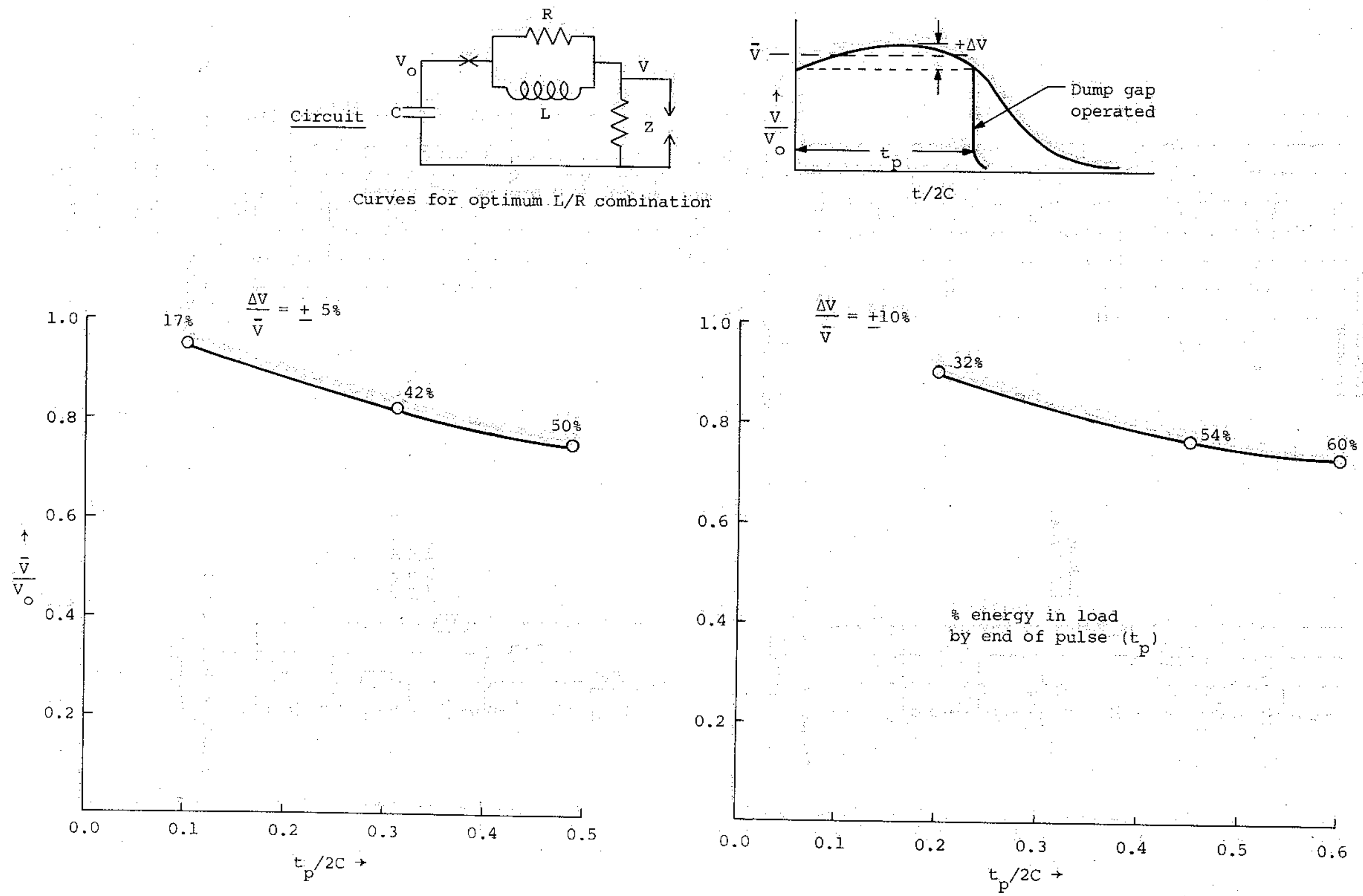
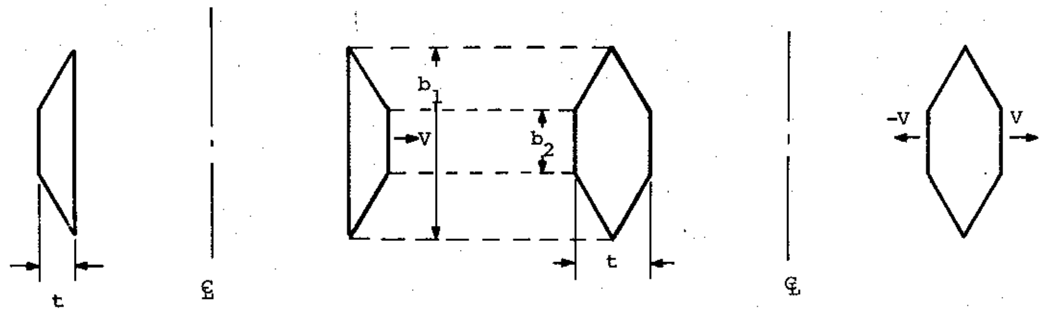

Circuit
V_o
C
R
L
V
Z
Curves for optimum L/R combination
$\bar{V}$
$+\Delta V$
$\frac{V}{V_o}$
t_p
t/2C
Dump gap operated
$\frac{\Delta V}{\bar{V}} = \pm 5\%$
$\frac{\bar{V}}{V_o}$
17%
42%
50%
1.0
0.8
0.6
0.4
0.2
0.0
0.1
0.2
0.3
0.4
0.5
$t_p/2C$ →
$\frac{\Delta V}{\bar{V}} = \pm 10\%$
32%
54%
60%
% energy in load by end of pulse (t_p)
0.6
$t_p/2C$ →

FIGURE 5



Cross section of windings   n turns ratio

Single sided output   Double sided output

Values of transformer parameters for single turn primary leakage inductance

$$L_e \approx \frac{72rb}{2b_1 + b_2} \text{ nH} \qquad L_e \approx \frac{18rb}{2b_1 + b_2} \text{ nH}$$

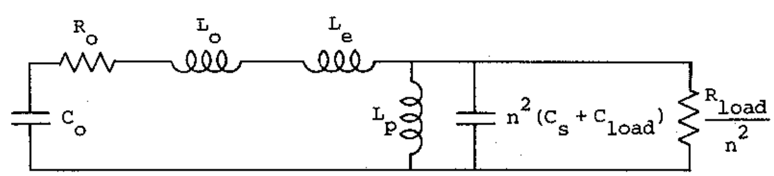
Primary inductance

$$L_p \approx \frac{40r^2}{r + b_1} \text{ nH}$$

Self capacity of winding

$$C_s \approx \frac{r(b_1 + b_2)}{t} \text{ pf}$$

Circuit



$$R_L \equiv \frac{L_o + L_e}{L_p} \qquad R_c \equiv \frac{n^2(C_s + C_{load})}{C_o}$$

$$C_{eff} \equiv \frac{n^2(C_s + C_{load}) + C_o}{n^2(C_s + C_{load})C_o}$$

$$\text{Gain} \approx \frac{2n}{1 + R_L + R_c} \times \frac{1 + e^{-\pi/2(R_c/Z)} + e^{-\pi/2(n^2 Z/R_{load})}}{3}$$

where $Z = [(L_o + L_e)/C_{eff}]^{1/2}$

Fast period $= 2\pi[(L_o + L_e)C_{eff}]^{1/2}$

Slow period $= 2\pi[L_p\{C_o + n^2(C_s + C_{load})\}]^{1/2}$

APPROXIMATE TRANSFORMER RELATIONS   FIGURE 6