Switching Properties of a Partially Set Square-Loop Ferrite Core

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***Abstract*—The switching properties of a partially set square-loop ferrite core depend not only upon the initial flux level, but also upon how that flux level was attained, and are therefore complex. Experimental results that describe some of this history dependence are presented. A thin-ring core ($OD/ID = 1.10$) was partially set by switching it from negative remanence ($-\phi_r$) to some flux level (ϕ_{ps}) using a rectangular PARTIAL SET pulse of duration T_{ps}. This pulse was followed by a rectangular TEST pulse having a variable amplitude F to determine the properties of switching from each partially set state. Three types of data were taken during the TEST pulse: 1) switching voltage waveforms [i.e., $\dot{\phi}(t)$] for a given ϕ_{ps} and F, with T_{ps} as a parameter, 2) peak switching voltage vs. F [i.e., $\dot{\phi}_p(F)$] curves for a given ϕ_{ps}, with T_{ps} as a parameter, and 3) $\dot{\phi}_p(F)$ curves for a given T_{ps}, with ϕ_{ps} as a parameter. The $\dot{\phi}(t)$ waveforms changed considerably as T_{ps} was varied, even though F and ϕ_{ps} were constant (e.g., peaking time was reduced from 0.5 μs to less than 0.1 μs as T_{ps} was reduced from 100 μs to 5 ns). The slope and threshold of the $\dot{\phi}_p(F)$ curves were lowered considerably as ϕ_{ps} was increased from $-\phi_r$ to $-0.36\phi_r$ (e.g., the slope was reduced by 40 percent and the threshold was reduced by 14 percent for $T_{ps} = 0.9$ μs). Presently used switching models are not able to account for these effects. Related phenomena also occur when the core is switched from $-\phi_r$ with an MMF which is not constant throughout the entire switching process. The experimental results are discussed relative to the future development of an appropriate switching model.**

Introduction

THE PHENOMENOLOGICAL switching properties of square-loop ferrite cores can be adequately described (for most purposes) by currently used switching models if switching is initiated from negative remanence $-\phi_r$. However, when the core is switched from a partially demagnetized state, secondary effects arise which are not described by these models. The existence of these secondary effects is generally known [1]–[5], but these effects have not been adequately described in the literature.

On the basis of domain wall switching as described by Menyuk and Goodenough [6], one would expect switching from a partially set state to be nearly a continuation of the switching which occurred during the preceding PARTIAL SET pulse except for the effect of differences in F. This is the first-order effect of partial setting and is accounted for by most switching models. The second-order effects are the primary subject of this paper.

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This study is complex because the switching properties are now history-dependent; i.e., these properties depend not only upon the initial flux level, but also upon how that flux level was obtained. This paper is restricted to the case in which the core is partially demagnetized with a single rectangular PARTIAL SET pulse. Once a core is partially set with a positive PARTIAL SET pulse, it can be switched in either the positive or negative direction. These two cases will be referred to as the positive-F and negative-F cases, respectively. We shall deal primarily with the positive-F case.

The secondary effects mentioned previously are also in evidence when a core is switched from negative remanence with a nonconstant MMF (e.g., MMF $= kt$, or a pulse having a rise time comparable to the core's switching time). This kind of switching, common in practical circuits, is closely related to the subject of this paper, but cannot be included except for brief comments.

The experimental measurements were taken on a thin-ring core ($OD/ID = 1.10$) so that geometry effects (radial variations of H) would not complicate the results. However, for convenience, the experimental results will be presented in terms of flux, ϕ, and MMF, F, rather than magnetization, M, and magnetic field intensity, H.

The emphasis of this paper will be on the properties of switching rather than on switching models; however, a specific model will be used as a convenient reference to which the data can be compared. This model will be described briefly. The experimental data to be presented do not depend on any particular switching model to reveal the qualitative switching properties of the core. However, the data were taken, and will be presented, from the viewpoint of future development of appropriate practical switching models. The basic physics responsible for the secondary effects of partial setting, although interesting and pertinent, is largely unknown and is beyond the scope of this paper.

The model to be used as a reference is the parabolic model, which describes $\dot{\phi}(\phi)$ with a parabola, and results in a sech [2] function for $\dot{\phi}(t)$ when F is a step funct'on. This model was chosen because it resulted in somewhat better agreement with experimental data than other models examined [7]. This model is also convenient in that both $\dot{\phi}(\phi)$ and $\dot{\phi}(t)$ are described by simple, easy-to-write functions. Unfortunately, the parabolic model has been derived only on the basis of rotational switching [8]–[10] which may occur at the higher H fields but is unlikely to occur at the very low fields where the model is still useful. This fact does not detract from the model's usefulness, but it does confuse our understanding of the basic physics of switching.

The parabolic switching model (or any other model) is usually described in the literature with 1) a linear dependence on the excess of H (or F) over a dynamic threshold H_o (or F_o), and 2) a final (maximum) value of magnetization (flux) independent of H (or F). Both descriptions are approximations and frequently are rather inaccurate. The form of the parabolic model to be used here has been altered in two aspects. First, the peak switching voltage $\dot{\phi}_p$ is made proportional to $(F - F_o'')^\nu$ where ν is an experimentally determined parameter (a typical value is 1.3). Second, the width of the base of the parabolic $\dot{\phi}(\phi)$ is varied by moving (horizontally) the positive termination of the parabola in accordance with a $\phi_d(F)$ function [ϕ_d is derived from the static $\phi(F)$ of the core]. The first modification is simple and very effective, and is not unique to this paper. The second modification [11], [12] which requires an analytical model for the static $\phi(F)$ curve, is somewhat more complex. The static $M(H)$ curve can be described by a hyperbola for most ferrite cores. This $M(H)$ function can than be integrated to obtain $\phi(F)$. This modified parabolic model can be written

$$\dot{\phi} = \lambda(F - F_o'')^\nu\left[1 - \left(\frac{2\phi + \phi_s - \phi_d}{\phi_s + \phi_d}\right)^2\right]. \qquad (1)$$

When F is a step function, (1) results in the $\dot{\phi}_p(F)$ equation

$$\dot{\phi}_p = \lambda(F - F_o'')^\nu. \qquad (2)$$

This model does not result in an initial spike when F is a step function, as is experimentally observed. This problem is not of direct concern here, but is currently under investigation.

Partial setting can be identified by three parameters, ϕ_{ps}, T_{ps} (or F_{ps}), and T_b, where ϕ_{ps} is the partially set flux level, T_{ps} and F_{ps} are the duration and amplitude of the PARTIAL SET pulse, respectively, and T_b is the period of time between the termination of the PARTIAL SET pulse and the initiation of the following TEST pulse [see Fig. 1(a)]. The experiments determine how switching properties from a partially set state are influenced by variations in ϕ_{ps} and T_{ps} (or F_{ps}). The effects of variations in T_b will be discussed only briefly [4]. Variations in T_b become effective only when its value is comparable to the duration of the negative tail in $\dot{\phi}(t)$ at the termination of the PARTIAL SET pulse.

Description of Experiments

General

The basic properties of switching from a specific partially set state can be determined from three types of experimental data: static $\phi(F)$ curves, $\dot{\phi}(t)$ waveforms for step-F drive, and $\dot{\phi}_p(F)$ curves for step-F drive.

The effects of variations in ϕ_{ps} and T_{ps} upon the static $\phi(F)$ curves [and therefore also $\phi_d(F)$ of (1)] are appreciable and important, but most of these effects are generally known and will, therefore, be considered only briefly. The $\dot{\phi}(t)$ waveforms for step-F drive will be examined for second-order effects of partial setting as T_{ps} is varied with ϕ_{ps} fixed. The $\dot{\phi}_p(F)$ curves for step-F drive will be studied, first as a function of T_{ps} with ϕ_{ps} fixed at $-1/2\ \phi_r$, and then as a function of ϕ_{ps} with T_{ps} fixed at 0.9 μs.

The measurements were all taken at a temperature of $30 \pm 0.5°$C. Flux measurements were made by integrating the $\dot{\phi}(t)$ with a second-order RC integrator [13] and measuring the output with a voltage reference and chopper on the input to the oscilloscope.

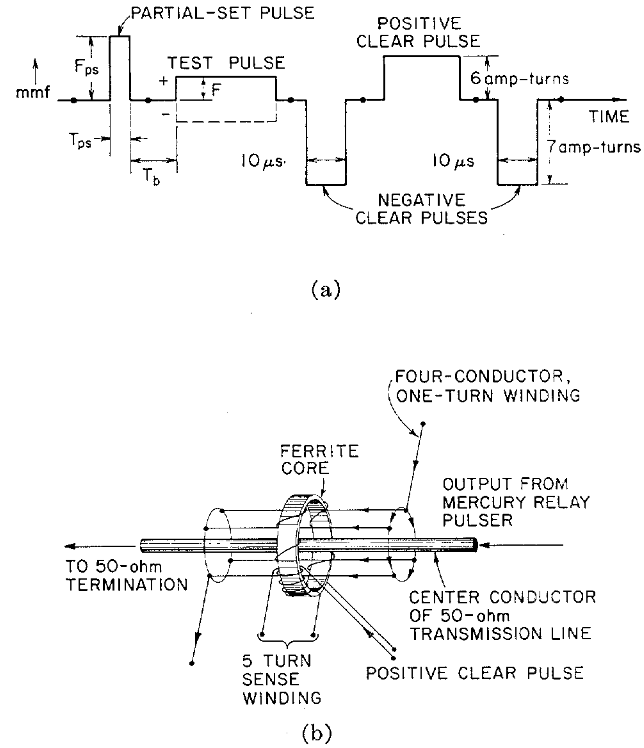

Fig. 1. Partial-setting experiment. (a) Pulse sequence. (b) Configuration of core and windings.

Core

All the experimental data included in this paper were taken on one toroidal core (I-4 in Nitzan and Hesterman [11]) which was ultrasonically cut from a half-inch disk of Indiana General 5209 ferrite. A batch of ten disks (with center holes) first were tested magnetically for uniformity, which was found to be good. A disk which was typical for the batch was then chosen for cutting core I-4. The geometry was toroidal with an OD/ID ratio of 1.10. This ratio was chosen as a compromise between 1) having radial variation of H and 2) having a high surface-to-volume ratio. The core's dimensions were: outer radius = 0.378 cm, inner radius = 0.343 cm, average radius = 0.360 cm, thickness along axis = 0.0848 cm. Two thin-ring cores made from other commercial materials also have been tested with qualitatively similar results.

Windings

The core was mounted coaxially in a 50-ohm transmission line so that fast-rise pulses could be applied via this transmission line [see Fig. 1(b)]. A distributed 10-turn winding was used for clearing the core. A one-turn winding, composed of four conductors in parallel and equally spaced around the center conductor of the transmission line, was used for applying the other pulses.

Pulse Sequence

The pulse sequence is shown in Fig. 1(a). The PARTIAL SET pulse switches the core from negative remanence to the desired partially set state. The TEST pulse then switches the core to determine its new switching properties. The $\dot{\phi}(t)$ and $\dot{\phi}_p(F)$ data were taken during the TEST pulse. The sequence of three CLEAR pulses then switches the core to $-\phi_r$. The positive CLEAR pulse is required to completely remove all history effects [3], [13], [14]. The TEST pulse had a 50-ns rise time. The PARTIAL SET pulse rise time $=$ 50 ns if pulse duration >0.9 μs; rise time <0.5 ns if duration ≤ 0.9 μs. The fast-rise pulse was supplied by a mercury-relay pulser having a maximum amplitude of 40 amperes.

Experimental Results and Discussion

Waveforms of $\dot{\phi}(t)$, with T_{ps} as a Parameter

One of the primary concerns in investigating the properties of switching from a partially set state is the $\dot{\phi}(t)$ waveform for a step-F drive. We wish to find the following information regarding the $\dot{\phi}(t)$ waveform: first, if it is nearly independent of F when normalized; second, if it can be described by a sech [2] function of time; and third, how it changes with ϕ_{ps} and T_{ps}. This information will determine the possibilities of retaining the parabolic switching model, possibly modified, to describe switching from a partially set state.

Oscillograms of $\dot{\phi}(t)$ were taken for ϕ_{ps} fixed at $-1/2\ \phi_r$ with $T_{ps} = 100$ μs, 0.9 μs, and 10 ns (corresponding values of F_{ps} were 30, 2.0, and 1.15 ampere-turns, respectively). These waveforms are superimposed in Fig. 2. The $\dot{\phi}(t)$ with no partial setting is also included for comparison. No significant changes in $\dot{\phi}(t)$ were noted as T_{ps} exceeded 100 μs or as T_{ps} decreased from 100 ns to 5 ns.

The most striking feature of Fig. 2 is the large change in $\dot{\phi}(t)$ with T_{ps}, even though the initial flux level, ϕ_{ps}, and the MMF, F, (during the switching) are constant. The entire variation in $\dot{\phi}(t)$ is due to differences in the speed of partial setting. These waveforms were compared to sech [2] functions of time. Good agreement was obtained if the height and width of the sech [2] function were freely adjusted and the front truncated; however, the parabolic model given by (1) and (2) does not allow that much freedom. In the model, the variation in $\dot{\phi}_p$ with F is controlled by λ, F_o'', and ν, but t_p cannot be adjusted independently, except by varying the initial flux level ϕ_{ps} and ϕ_d, both of which are constant for Fig. 2. Thus,

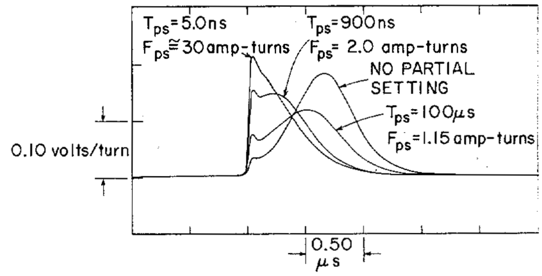

Fig. 2. Effects of T_{ps} on $\dot{\phi}(t)$ of core I-4. $F = +2.50$ ampere-turns, $T_b = 50$ μs, $\phi_{ps} = -1/2\ \phi_r$.

even though the model gives $\dot{\phi}(t)$, which agrees with the shape of the experimental waveforms, it is not capable of describing the variation in t_p shown in Fig. 2. It has been found [13] that the parabolic model can be modified so as to handle the changes in t_p by introducing an additional parameter ϕ_c. We are then left with the additional problem of determining ϕ_c as a function of ϕ_{ps}, F_{ps} (or T_{ps}), T_b, and F. The physical meaning of ϕ_c is unknown.

When the parabolic model of (1) and (2) is so modified it becomes

$$\dot{\phi} = \lambda(F - F_o'')^{\nu}\left[1 - \left(\frac{2\phi + 2\phi_c + \phi_s - \phi_d}{\phi_s + 2\phi_c + \phi_d}\right)^2\right]. \quad (3)$$

Note that the function $\dot{\phi}_p(F)$ given by (2) still applies. The function $\phi_d(F)$ also needs to be altered, but the resulting function has not yet been determined. The influence of ϕ_c upon calculated $\dot{\phi}(\phi)$ and $\dot{\phi}(t)$ for step-F drives are shown by plots in Nitzan and Hesterman [11] and in Hesterman [13]. The major influence of ϕ_c is to affect t_p and the initial value of $\dot{\phi}$ just after the initial spike. However, ϕ_c does not influence the total flux switched [area of $\dot{\phi}(t)$] nor the value of $\dot{\phi}_p$.

The functional relationship $\phi_c(\phi_{ps}, F_{ps}, T_b, F)$ has not been determined entirely yet, but some of its aspects have been studied [11], [13]. The function $\phi_c(F_{ps})$ for a constant ϕ_{ps}, T_b, and F was roughly determined for the thin-ring core used in Hesterman [13] (core E-6, made of telemeter T-5 material). The values of ϕ_{ps}, T_b, and F were $-1/2\ \phi_r$, 50 μs, and 2.00 ampere-turns, respectively (F_o'' was about 1.0 ampere-turn). For F_{ps} just over threshold, ϕ_c was equal to about $-0.2\phi_s$. As F_{ps} increases, ϕ_c increases through zero and then levels off at about $+0.2\phi_s$ for very large F_{ps} values. In the case in which $T_b = 0$ (i.e., no separation between the PARTIAL SET and TEST pulses), the value of ϕ_c must be zero for $F_{ps} = F$, because this corresponds to switching from $-\phi_r$ with a single step-F drive.

Since ϕ_c becomes relatively large for $F_{ps} \gg F > 0$ and $\phi_{ps} \gg -\phi_r$, t_p (time required for $\dot{\phi}$ to reach its peak) decreases to the point that $\dot{\phi}_p$ is lost in the tail of the initial spike or may even go negative. For $\phi_{ps} > -0.3\ \phi_r$ and $F_{ps} > 2.5$ ampere-turns ($T_{ps} < 0.5$ μs), it is difficult to measure $\dot{\phi}_p(F)$ curves. Even if $\phi_c = 0$, $\dot{\phi}_p$ will disappear for $\phi_{ps} > 0$ because the first half of switching has already been completed. Therefore, the $\dot{\phi}_p(F)$ curves for a positive

TEST pulse were taken mostly at $\phi_{ps} < -0.3\phi_r$ and for $F_{ps} < 2.5$ ampere-turns.

When the experiment of Fig. 2 is repeated for ϕ_{ps} nearer to $-\phi_r$, smaller changes occur as T_{ps} is varied. The maximum and minimum values of ϕ_c (for $F_{ps} = F_o''$ and ∞, respectively), therefore, increase with ϕ_{ps}. This function has not been determined experimentally. The entire topic of ϕ_c requires further investigation.

When F is negative, two $\dot{\phi}(t)$ effects are observed: first, the waveform is not accurately described by the parabolic model because of a considerably larger tail on the initial spike, and second, there is little variation in t_p as a function of F_{ps}. Because of the first item, the modeling of switching for negative-F switching is considerably more complicated than for positive-F switching. Because of the second item, $\dot{\phi}_p(F)$ curves can be taken for much larger values of F_{ps} and ϕ_{ps} than could be taken for the positive-F case. Experimental $\dot{\phi}_p(-F)$ data are given in Nitzan and Hesterman [11].

Peak Switching Voltage vs. MMF

Information on the variation of switching speed with drive MMF is generally obtained by measuring 1) reciprocal switching time, $1/\tau_s$, vs. F, or 2) peak switching voltage, $\dot{\phi}_p$, vs. F. There are important advantages and drawbacks to either method [13]. However, one factor is decisive. An examination of (3) shows that $\dot{\phi}_p$ depends only on F_o'', λ, and ν as far as the model is concerned; i.e., as far as first-order effects are concerned. In contrast, the switching time, τ_s, as determined from (1), depends not only on F_o'', λ, and ν, but also on ϕ_c (a second-order effect) and on the initial flux level, ϕ_{ps} (a first-order effect). The determination of F_o'', λ, and ν from $\dot{\phi}_p(F)$ data is, therefore, a simple, straightforward process. It would be difficult to determine these three parameters and to resolve the various effects of partial setting using $1/\tau_s$ vs. F data.

Experimental $\dot{\phi}_p(F)$ curves were taken for two cases: with ϕ_{ps} as a parameter and T_{ps} constant, and with T_{ps} as a parameter and ϕ_{ps} constant. To simplify the experiment, in both cases, T_b was made large compared to the relaxation time of $\dot{\phi}$ following the termination of the PARTIAL SET pulse. The values of F_o'', λ, and ν were determined for each $\dot{\phi}_p(F)$ curve so that the relationship of these parameters could be studied as a function of ϕ_{ps} and T_{ps}. These values were used in (2), which was plotted for comparison with the experimental points.

The $\dot{\phi}_p(F)$ curves with ϕ_{ps} as a parameter are shown in Fig. 3. The two most obvious effects are a monotonic decrease in both the threshold and slope as ϕ_{ps} increases from $-\phi_r$ to $-0.365\ \phi_r$. The leftward shifting of the $\dot{\phi}_p(F)$ curves corresponds to a decreasing F_o'', and the decreasing slope corresponds primarily to a decreasing λ. The decrease in λ is over 40 percent, which is a very substantial effect. The net result is that a $\dot{\phi}_p(F)$ curve for one value of ϕ_{ps} crosses a curve for a different ϕ_{ps}. The crossing point is seen to vary only a small amount as ϕ_{ps} increases. Hence, we have two opposing effects; the decrease in F''_o tends to increase the switching speed, whereas the decrease in λ tends to decrease switching speed. Which effect predominates depends on the value of F relative to the crossing point. If F is less than F at the crossing point, e.g., 1.5 ampere-turns (Fig. 3), $\dot{\phi}_p$ will increase as ϕ_{ps} increases from $-\phi_r$ (in this case, the decrease in F_o'' predominates). On the other hand, if F is greater than F at the crossing point, e.g., 4 ampere-turns, then $\dot{\phi}_p$ will decrease as ϕ_{ps} increases from $-\phi_r$ (in this case, the decrease in λ predominates).

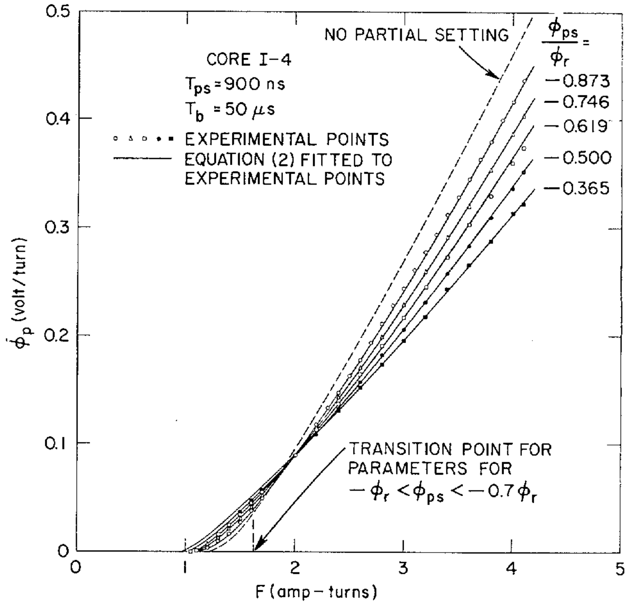

Fig. 3. $\dot{\phi}_p\ (+F)$ with ϕ_{ps} as a parameter.

The decrease in F_o'' is qualitatively consistent with the well-known decrease in threshold as observed on a static $\phi(F)$ curve. The decrease in the slope of the $\dot{\phi}_p(F)$ curve has not been generally recognized.

The values of F_o'', λ, and ν were determined for each value of ϕ_{ps} by plotting $\dot{\phi}_p(F - F_o'')$ on log-log paper. For this particular core, and for ϕ_{ps} near $-\phi_r$, the $\dot{\phi}_p(F)$, curves had to be broken into two regions, each having a different set of values of F_o'', λ, and ν. The curve of Fig. 3 for no partial setting makes a transition at $F = 1.62$ ampere-turns. Although the parameters for the two segments are different, the curve and its first derivative are continuous at this transition. The values of F_o'', λ, and ν are plotted vs. ϕ_{ps} in Fig. 4. As ϕ_{ps} increases from $-\phi_r$, the two sets of values of parameters approach each other. The error bars were estimated by determining how much F_o'' could be changed before a noticeable curvature could be seen in the log-log plot of $\dot{\phi}_p$ vs. $(F - F_o'')$.

The value of F_o'' for $F < 1.62$ ampere-turns (i.e., below the transition) decreases only slightly as ϕ_{ps} increases. For $F < 1.62$, ν seems to decrease considerably as ϕ_{ps} increases; however, the error bars are large so that this curve can be only roughly determined. For $F > 0.62$, ν varies little with ϕ_{ps}. These curves appear to level off as ϕ_{ps} exceeds $-1/2\ \phi_r$.

The $\dot{\phi}_p(F)$ curves with T_{ps} as parameter and ϕ_{ps} fixed are shown in Fig. 5. Here again it is clear that F_o'' and

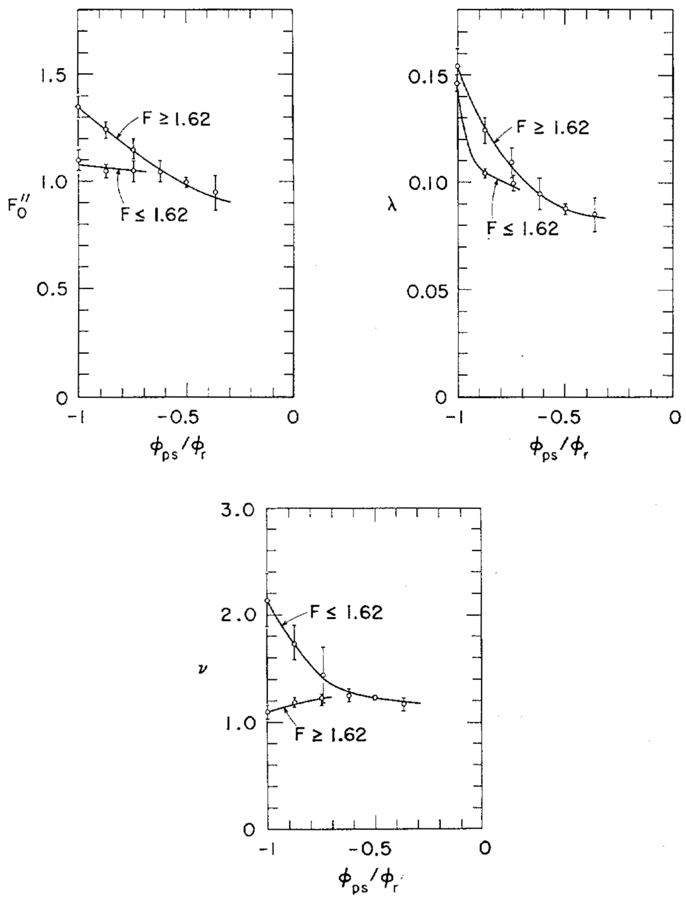

Fig. 4. F_0'', λ, and ν vs. ϕ_{ps}. Core I-4, $T_{ps} = 900$ ns, $T_b = 50$ μs.

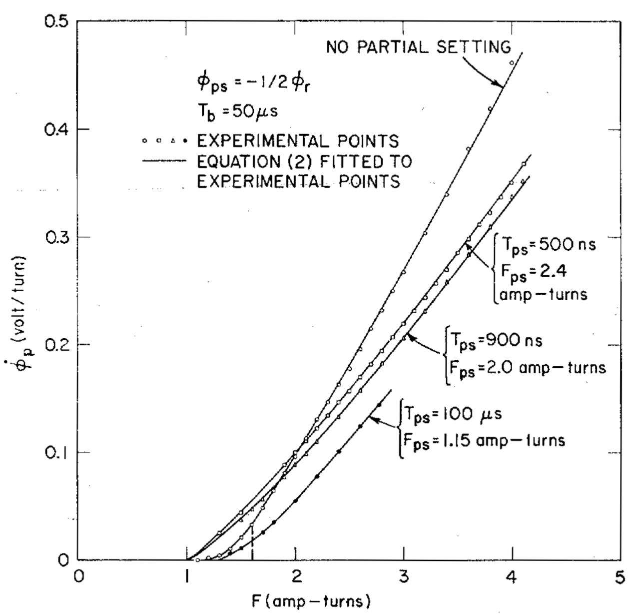

Fig. 5. $\dot{\phi}_p$ $(+F)$ of core I-4 with T_{ps} as a parameter.

λ have been decreased by partial setting. The values of F_o'', λ, and ν vs. T_{ps} are not included. However, it can be seen that F_o'' decreases somewhat as T_{ps} decreases, and that λ is nearly independent of T_{ps}. Measurements taken on another thin-ring core (E-6) [13] showed similar effects, except that F_o'' decreased more markedly as T_{ps} decreased below 1 μs. This core (E-6) also gave similar effects with regard to static $\phi(F)$ and $\dot{\phi}(t)$.

The $\dot{\phi}_p(F)$ data were also taken for negative-F (see Fig. 1), but are included elsewhere [11]. The most important effects observed were that F_o'' decreased moderately as a result of partial setting, as for positive-F; but the decrease in λ as a result of partial setting was much smaller than for positive-F. Therefore, the $\dot{\phi}_p(F)$ curves for negative-F were more generally above the no-partial-setting curve than for positive-F. Thus, switching speed for a negative TEST pulse is generally increased by partial setting (for a positive TEST pulse, switching speed is generally decreased by partial setting).

Reducing T_b (Fig. 1) to zero resulted in only a relatively small change in the $\dot{\phi}_p(F)$ curves, except at very large values of F and F_{ps}. Thus, λ and F''_o are significantly lowered by partial setting even for $T_b = 0$. When $T_b = 0$, $F(t)$ effectively makes a step up or down during the process of switching (no interruption in switching). For either $F > F_{ps}$ or $F < F_{ps}$, switching after the step (i.e., during the TEST pulse) corresponds to a different $\dot{\phi}_p(F)$ curve of lower slope and threshold (lower λ and F_o''). This new $\dot{\phi}_p(F)$ curve crosses the no-partial-setting $\dot{\phi}_p(F)$ curve at $F = F_{ps}$ ($T_b = 0$ and $F = F_{ps}$ corresponds to the case in which the MMF is constant throughout the entire switching process). Thus, if $F > F_{ps}$, and $\dot{\phi}_p$ occurs during the TEST pulse, $\dot{\phi}_p$ will be less than the no-partial-setting $\dot{\phi}_p$ at the same value of F. If $F < F_{ps}$, and $\dot{\phi}_p$ occurs during the TEST pulse, then $\dot{\phi}_p$ will exceed the no-partial-setting $\dot{\phi}_p$ at the same value of F. The magnitude by which $\dot{\phi}_p$ is decreased by a step up (or increased by a step down) relative to no partial setting depends on 1) size of the step, 2) F_{ps}, and 3) $\Delta\phi_{ps}$ (the flux switched prior to the step). The switching time τ_s, after the step change in MMF, depends on the change in ϕ_c, in addition to the above factors.

The general conclusion to be drawn from the above considerations of $T_b = 0$ is that the values of λ and F_o'' determined from step-F switching are correct only for step-F switching. Apparently, λ and F_o'' decrease during the switching process, but their effects are mutually cancelling with respect to $\dot{\phi}$, except when the MMF varies during the switching process. This concept has important implications concerning the development of a general model capab'e of accurately describing switching for an arbitrary $F(t)$.

The general case in which $F(t)$ varies smoothly is a generalization of the above $T_b = 0$ case. It seems probable that switching for a monotonically increasing function would also give a lower value of $\dot{\phi}_p$ than that calculated from the model using parameters determined from step-F switching. This has been verified experimentally. For example, a core was switched with a ramp MMF ($F = kt$). The curve of $\dot{\phi}_p(k)$ was (about 15 percent) lower than the curve calculated by using parameters determined from step-F switching (t_p was also in error). Most of these errors could be removed for any slope k by decreasing λ about 25 percent and F_o'' about 40 percent. Similarly, one would expect higher values of $\dot{\phi}_p$ than calculated from the model for a monotonically decreasing $F(t)$. This has not yet been experimentally verified.

Conclusions

It is generally known that partially setting a core results in secondary effects which are not entirely consistent with the concept of domain wall switching as described by Menyuk and Goodenough [6]. It is concluded that the functional form of $\dot{\phi}_p(F)$ is not altered by partial setting, but its parameters are altered (at least for some ferrite cores). The $\dot{\phi}(\phi)$ function is still parabolic for positive-F switching from a partially set state, but the parabolic function must be modified [e.g., ϕ_c introduced, as in (3)] to account for the effects of variations in F_{ps}. For negative-F switching at low values of F, the $\dot{\phi}(\phi)$ curve is no longer parabolic.

The threshold, F_o'' of the $\dot{\phi}_p(F)$ curve is lowered significantly by partial setting for large F_{ps} values. The value of F_o'' depends on both ϕ_{ps} and F_{ps}. The coefficient λ of the $\dot{\phi}_p(F)$ curve is lowered considerably by partial setting (e.g., 40 percent for $\phi_{ps} = -1/2\ \phi_r$). The value of λ depends primarily on ϕ_{ps}. It is relatively independent of F_{ps}.

The physical mechanisms responsible for these secondary effects of partial setting are mostly unknown. These effects are appreciable for all switching speeds. At very slow switching speeds, switching is almost surely by domain wall motion. Thus, a need exists for a new physical model of domain wall switching, or at least extensive modifications of the existing models. It is hoped that these experimental data will prove useful in the development of new physical switching models.

The use of switching models for analyzing circuits which contain square-loop ferrite cores does not depend upon our knowledge of the physical mechanisms of switching. To develop practical switching models capable of accounting for partial-setting effects, there are three basic approaches which can be followed, listed here in the order of increasing difficulty and generality.

1) If the core is always switched from $-\phi_r$ with a particular $F(t)$ function, the parameters of the *existing* parabolic model [see (1)] can possibly be determined for that specific function (e.g., experiments for $F = kt$ indicate that only λ and F_o'' need be corrected to give satisfactory corrections for all values of k).

2) If the core is switched from known partially set states with a nearly constant MMF, the model of (3) can be used, providing corrected values of ϕ_c, λ, F_o'', ν (possibly), and the function $\phi_d(F)$ can be determined (or approximated) as functions of ϕ_{ps}, F_{ps}, and (possibly) T_b.

3) If the core is switched from $-\phi_r$ with various arbitrary $F(t)$ functions, a *new* model must be developed which accounts for the secondary effects of a nonconstant $F(t)$.

Future investigation is most needed in two areas: 1) $T_b = 0$, and 2) a negative TEST pulse. Experimental data are also needed for other ferrite materials, other temperatures, and other methods of partial demagnetization so that the general and specific effects can be resolved. Considerable investigation remains to be performed before all the effects of partial setting are revealed and described by practical switching models. However, the prospects for the eventual realization of this goal appear promising.

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