Primary and Induced Currents from Cable Discharges

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***Abstract*—Analysis of cable discharge events (CDE) starts with the basic wire-to-ground pulse and continues, for shielded cables, with induced currents on the signal lines. These situations can be classified and analyzed through step response and impulse response. The essential behaviors can be derived from the uniformly charged shield being grounded to produce induced current on the data lines at the opposite end. This effect is called the W-pulse and is shown to be a kind of step response for both loads. From this and similar results, the effects on shielded cable lines of the commonly-applied IEC 61000-4-2 platform pulse are derived by convolution. Finally, the induced currents resulting from a charged shielded cable above a ground plane are deduced.**

Because the coupling from shielded cables to internal lines is almost all inductive, we have bipolar induced pulses with zero charge integral. Thus the bipolar data line response to these shielded cable pulses is a significant hazard for pulsed latchup. We discuss adequacy of the low-voltage IEC direct pin pulse (often called direct pin zap or DPZ) for assessing pulsed latchup on external ports, shielded in particular. Finally, it is shown why having connected cables as part of the regular IEC platform test also helps to test for cable discharge latchup hazards.

I. Introduction

Under the right circumstances, platform cable discharge events have the potential for creating problems for the information technology equipment manufacturer and its customers. Most failure events causing lockup or destruction are likely to be caused by a transient latchup event that happens to a silicon component on the platform (i.e., usually laptop or desktop PC) when a cable already connected to that platform undergoes an ESD pulse to the cable shield (nearly all external connections to chips are through shielded cable interfaces). The options include USB cable, VGA cable or even a mouse. USB and VGA events can include the case of a floating, battery-operated laptop, in operation, having its cable connected to a grounded printer or other cable recipient at a drastically different potential compared to the platform. In the case of a mouse, a charged user would touch a connected mouse on a powered up system. The result in all these cases might be lockup or worse, including latchup-induced destruction of the silicon component. As a point of clarification, it is expected that these silicon components would have passed all the product qualification DC latchup requirements.

Platform ports with Ethernet twisted pair connections are not shielded and suffer the full impact of the cable discharge. These are usually the only computer platform ports to which the full (primary) CDE pulse applies, and so the complete path through the transformer and board to chip inputs must be considered. Even so, the discharge waveform is essentially the same as the shielded cable pulse that we will use as a starting point in this work. The newest entries for the computer platform are HDMI, SATA and USB3 ports, all having shielded cables as part of the standard. The shields of these cables (and possibly some power supply lines, when they are preferentially placed to connect first) will feel the primary CDE pulse, not the interior data lines.

The simplest kind of shielded cable pulse [1] has the shield artificially charged uniformly, data lines at the discharge end are still open, and the induced current propagates to the far end, the connected end, thus stressing the pins on the chip at the end of the connected line. Meanwhile, at the discharge end, there is a pulse resembling the IEC 61000-4-2 chassis test, so any weaknesses there can be investigated accordingly. The shield then protects the data lines on the connected port, as expected. However, because shields do have some amount of inductive leakage, the pulse is a transformed, bipolar version of the shield pulse itself, although muted. In this work we examine this case, plus other likely CDE cases, in further detail.

II. Primary Shield or Wire Pulse

Our eventual strategy will be to find an impulse response that describes the induced currents on shielded signal lines, and apply it to the basic pulse experienced by the shield. The shield (or Ethernet wire) pulse presumes a potential between cable and platform, with perpendicular geometry the most likely real-world situation. In this case the charge bunches up toward the front of the cable, the characteristic impedance becomes a function of height z, increasing along the axis of the cable as one moves away from the ground plane. The solution of charge density along the cable was treated in [2], and can be approximated pretty well from [3]; Fig. 1 shows the essentials. There is a log-based taper of charge density, and therefore impedance, along the z-axis. Fig. 2 graphs the charge density for constant voltage on the post, or cable shield. Once the shield is touched to ground, the distance axis turns into a time axis, aside from reflections owing to a tapered source impedance. With a constant spark impedance and this tapered source impedance, the current vs. time solution is

2010 IEEE Electromagnetic Compatibility Symposium, Ft. Lauderdale, FL, July 25-30, 2010

essentially the same as for the step response of the infinite cylindrical antenna [4], and resembles Fig. 2. Finite cable length results in reflections, radiation, and a wave series, but the strongest effects are of course in the first time step. Now that we have a shield current waveform, we should be able to deduce much about the coupled signal on the inner line, because the cable has uniform internal impedance.

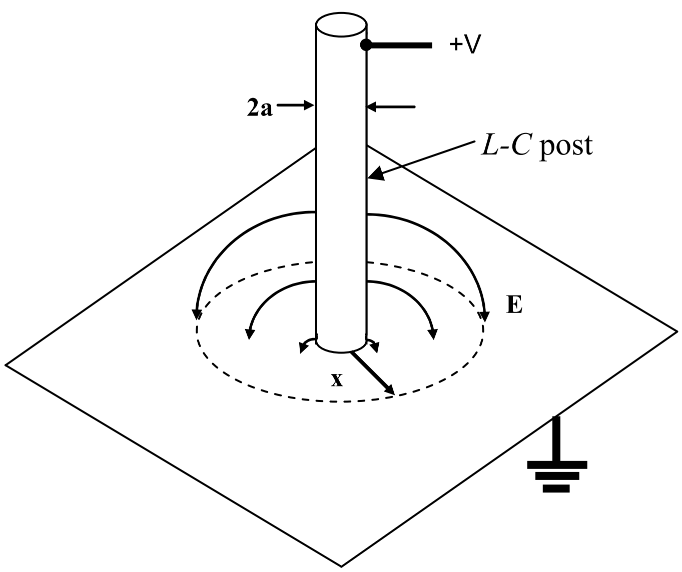

Fig. 1. Cable shield or wire as *L-C* post, with its electric field before discharge, as in [2].

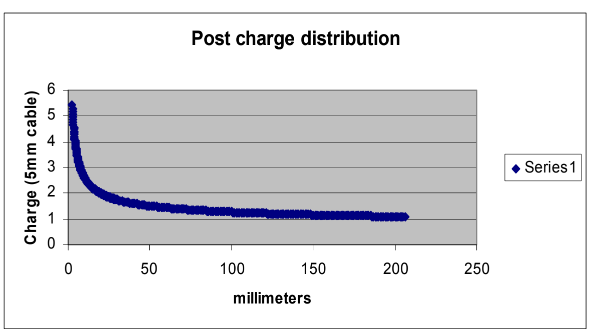

Fig. 2. Log-tapered charge distribution on a vertical shield or post of 2a=5 mm diameter, held at a constant potential perpendicular to a ground plane as in Fig. 1. With the height axis converted to time, this also generally describes the current pulse at the spark when the shield touches ground, and it describes the declining size of the current step with height as the hemispherical wave propagates upward.

III. TYPES OF SHIELDED CABLE PULSES

We can classify the four basic CDE events we want to examine, shown in Table I. Let the platform with our product under stress be the "Near End" (NE) element, although in Case 3 we're also interested in what the "Far End" (FE) feels when the NE is pulsed. Case 1 is from [1] as discussed above and the other three events are done with an IEC generator applied to the shield at the platform (3 and 4) or at the open end (2). The IEC pulse here is not to be confused with a Direct Pin Zap (DPZ) test, where the shield is bypassed and the data pins are stressed with an IEC pulse of reduced voltage. The shield-induced IEC events here could occur in ordinary IEC 61000-4-2 chassis testing and are highly relevant; we'd like to determine if the induced currents could approximate Case 1 (as in Case 1A) and also compare with DPZ. At present, DPZ can check a component for Case 1 vulnerability, but there could be better options.

Our approach will, essentially, be to examine the five stresses (last column, Table I) that result from these four cases. Case 1A is so named because we liken it to Case 1 and attempt to calculate the IEC response from the transfer function (impulse response) determined for Case 1. Thus there will be only four distinct stresses, or eigenpulses. For Case 3, where another platform is already connected and a chassis pulse is launched onto the cable shield as well, components at either or both NE and FE platform connections could be damaged, so we're interested in both responses.

Case	Platform status	Near End cable	Far End cable	Pulse	Stresses
1	charged	connected	open	FE to ground	NE
1A	ground	connected	open	IEC to FE shield	NE
2	ground	connected	open	IEC to NE chassis	NE
3	ground	connected	connected	IEC to NE chassis	NE, FE

Table I. Four CDE cases of interest, for which there will be five distinct stress responses.

A. *Case 1*

The work of [1] treated Case 1 comprehensively, and supported results with coupled line simulations and lab data. However, the case was not generally recognized as a step response, from which an impulse response could be determined and more general conclusions drawn. In [1], the cable shield had uniform external impedance to earth ground, and impedance matching was such that multiple reflections did not take place. The result therefore (called the **W-pulse** in [1]) was what we will also call an "eigenpulse", meaning that it describes the essentials of the response under perfect conditions, and represents an impulse or step response. Impedance mismatches and such may cause pulse trains of declining amplitude, but their essence is captured in the eigenpulse. Fig. 3 shows how we created the W-pulse using triaxial cable; in the case of perfect Z-matching, Zair (outer cable impedance) would match Zfe and Zne would match Zwire, the inner cable. The lab result is shown in Fig. 4, where the W-pulse is clear even though mismatches cause a pulse train. As discussed in [1], Fig. 4 shows negative effective inductance due to the sign of the response, but that is a familiar result of braid inductance versus hole inductance.

Fig. 5 shows the essential construction of the W-pulse, with symmetry, zero integral (due to charge balance for inductive-only coupling) and simple timing relationships determined by the round-trip transit times on the fast (outer) and slow (inner) transmission lines. The coupled line simulations and insight recorded in [1] about the W-pulse allow us to realize exactly what is going on with inductive coupling (Fig. 6) with respect to a propagating step. Inductive coupling causes equal and opposite charge quantities to be launched in opposite directions on Line 2 (center conductor, or internal data lines) at each point passed by the propagating shield current step on the outer line (Line 1). Then with the two contrasting line velocities, the makeup of the W-pulse becomes a simple linear system step response as described in the timing sequence of [1]; other pulse responses become obvious. The W-pulse as described thus far is now seen as a step response, as shown in Fig. 7. With the step applied between the resistive ground and the floating line, and Zair matched to Zfe, the W-pulse is created just as it is with the matched discharging line of Fig. 3 and is equivalent. The transfer function, or impulse response, for the NE cable response is therefore the differentiated step response. That impulse response is shown in Fig. 8, a sequence of four delta functions; we'll call it **W**(t), and we next use it to consider the response to IEC pulses.

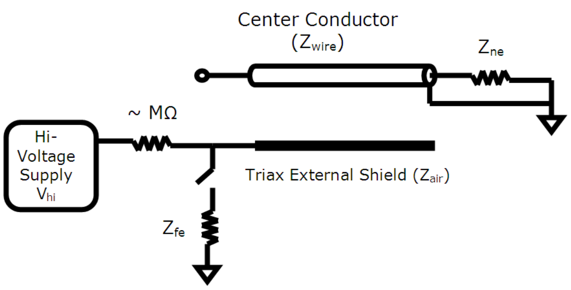

Fig. 3. Lab setup (from [1]) for creating the Case 1 W-pulse using triaxial cable. Outer line has constant impedance and simulates real world air line.

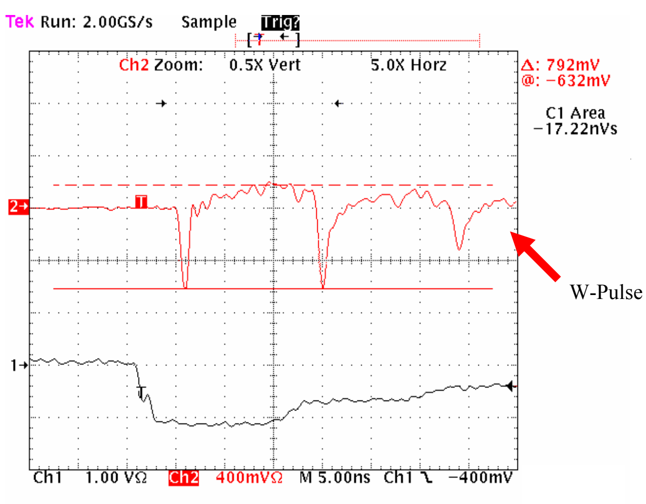

Fig. 4. W-pulse using Fig. 1 lab setup. Air line pulse shown in black, trace 1; ideally it would be a rectangular pulse imperfect Z-matching gives waveform shown and some multiple reflections. Even so, the first time step shows the W-pulse, trace 2 in red.

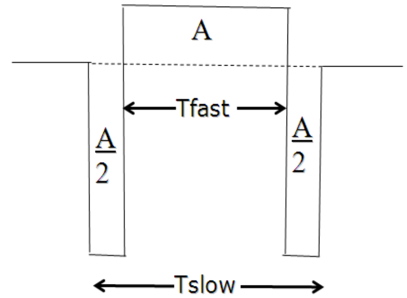

Fig. 5. Ideal Case 1 W-pulse for Z-match at far end (FE) on air line and Z-match on near end (NE, platform) cable line, other connections open (Fig. 3). Data lines at NE feel this. Areas balance due to inductive-only coupling. Tfast is round trip delay of fast (air) line, Tslow is round trip delay of slow (dielectric) line. Sharp spikes are due to the pileup of forward coupled waves.

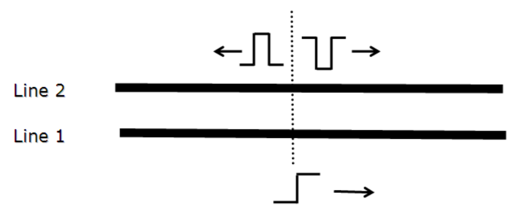

Fig. 6. Conceptual view of (relatively weak, positive inductance) inductive-only coupling between two transmission lines for a step input. For our cases, if the step represents the current on the outside of the shield for the air line (Line 1), the induced current at each point on the dielectric line (Line 2) flows in a direction consistent with Lenz' Law but consists of an equal and opposite pair of forward and backward waves along the dielectric line. This consideration is sufficient to generate the step response of the system.

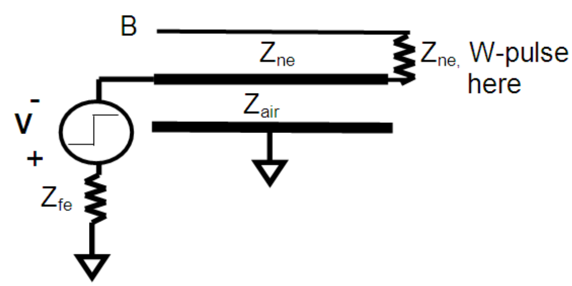

Fig. 7. Step response view of Case 1, W-pulse, felt at data lines on Zne. Zair matches to Zfe for eigenpulse, dielectric line matched at NE and open at point B. For the initially charged Zair as in Fig. 3, superimpose this step with the initial +V on Zair and you have W-pulse on Zne and square pulse on Zfe, identical to Fig. 3.

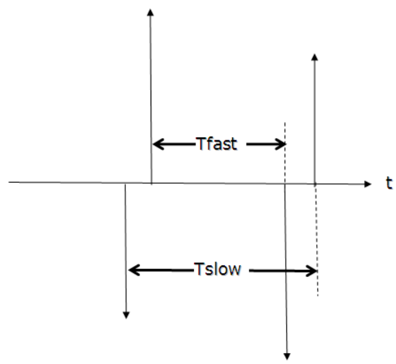

Fig. 8. Impulse response **W**(t) of near end as in Case 1 Figures 3 and 7; derivative of W-pulse with relative strength of delta functions shown.

IV. Other Cases of Shielded Cable Pulses

A. *Case 1A*

Case 1A is where we want the connected platform (NE) response to a FE pulse, with the IEC generator, on the open cable shield. In the IEC test, the shield-to-ground line is formed by the placing the cable on the horizontal coupling plane, so uniform outer line impedance is probably correct. The basic Case 1 situation (Fig. 7) still applies, as the FE of the cable shield is connected to the pulse source, the IEC generator. While the source resistance will not likely match the outer line impedance and it is understood there will be multiple reflections, the basic initial response at the NE to a FE pulse with the IEC generator can be computed. If f(t) is the IEC current waveform [5] and **W**(t) is the impulse response as in Fig. 8 and discussed above, basic network theory tells us the NE response is found through convolution:

$$NE(t) = \int_0^\infty f(\tau)\,\mathbf{W}(t-\tau)\,d\tau \tag{1}$$

The result is pictured in Fig. 9 for a 1m cable and v/c of 1 and 0.67 on the air line and cable line respectively. The NE(t) response will change with cable parameters, particularly cable length, but the f(t) is of course constant. The current from the (unipolar) IEC waveform is seen to be bipolar, with very sharp beginning and ending pulses owing to the features of the impulse response of the cable. This bipolar pulse could very definitely be a system latchup hazard on a powered-up system. As the IEC test is routinely applied at many kilovolts to grounded metal at the platform, this Case 1A stress is clearly a legitimate IEC 61000-4-2 chassis pulse, but requires the IEC generator to be applied to the shield on the end of an attached, open cable. For an aggressive, worst-case test, the IEC generator could be applied to a "leaky" cable, i.e., one with extra inductive holes in it so that more signal is coupled.

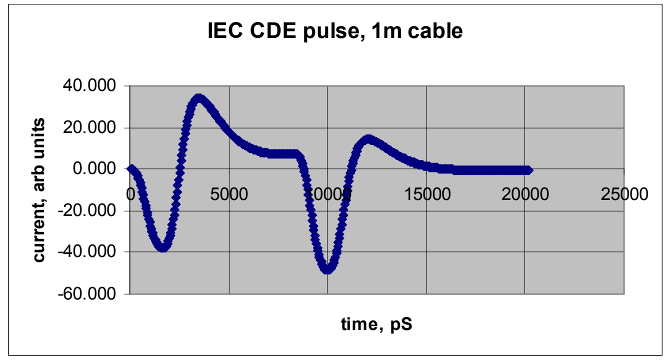

Fig. 9. Convolution result (Eq. 1) for Case 1A, IEC pulse applied to FE open end of cable shield and signal at NE platform data lines shown. 1 meter cable; v/c=1 for air line and 0.67 for dielectric line. The main convolution effect is bipolar pulse pairs, produced as each spike doublet (Fig. 8) sweeps across the leading section of the IEC pulse. For 1m, Tfast=6.7 nS and Tslow=10 nS.

B. *Case 2*

In Case 2, there is a near-end pulse to the shield and a near-end connection to feel the effect, while the far ends are open (Fig. 10). Our target stress is the IEC pulse to the chassis at the cable, of course, whereby we again use the impulse response and convolution to calculate what the data lines feel in common mode. All we need in addition to the procedure stated above is the impulse response for this situation, best found as the derivative of the step response. With the insight of Case 1 above, and the analysis of the Case 1 W-pulse along with the inductive-only coupling principle of Fig. 6, it is possible to write down the NE step response of Fig. 10 as shown in Fig. 11. This is a distinctly different eigenpulse from the W-pulse of Fig. 5, but the time scales are familiar. Because of its shape, we could call it the **notch pulse**, because of the short deep notch between the two long pulses. Impulse response again is the derivative, four impulses but having magnitudes and timings to match Fig. 11. Convolution to give the result of an IEC pulse to the shield where it joins the chassis is straightforward and follows Case 1A. Bipolar pulse effects resembling Fig. 9 result.

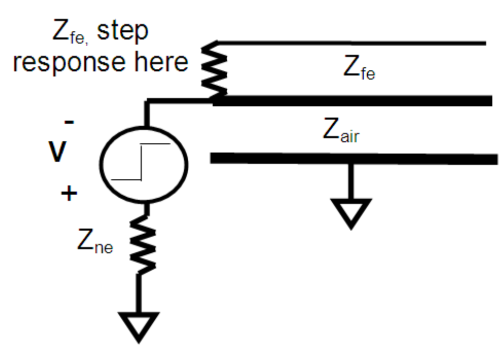

Fig. 10. Case 2 step response situation; Zair=Zne and Zfe match for eigenpulse. Pulse is applied to platform chassis at shield connection (near end), cable far end open. Current is induced on platform data lines and into platform load Zfe.

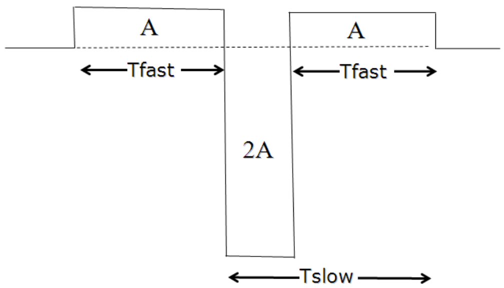

Fig. 11. Case 2 step response at Zfe load (notch pulse) for situation shown in Fig. 10.

C. Case 3

The final case in this series from Table I is that of a shielded cable already terminated at both ends, with a pulse applied to the shield at the chassis at one end (Fig. 12). Data lines at both ends will feel something. This could happen with the IEC pulse applied as in Case 2 but with the far end already connected to a peripheral, a camera or music player for example. The step responses for this configuration can also be worked out by comparison with other cases and are shown in Fig. 13 for near end and far end; aside from the obvious time delay to far end, they are mirror images of each other. From their shape, we call them **L-pulses**, with the L shape being flipped to convert L_{ne} into L_{fe}. Impulse response now has three delta spikes, as each pulse is like the left or right half of a full W-pulse. Convolution with the IEC waveform again results in a bipolar pulse, generally similar to Fig. 9.

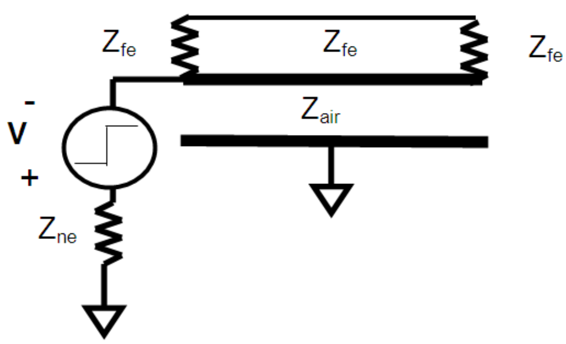

Fig. 12. Case 3 step response situation; Zair=Zne and Zfe matched at both ends of dielectric line for eigenpulse. Pulse is applied to platform chassis at shield connection (near end). Current is induced on platform data lines and into platform loads Zfe but the pulses differ due to the step being at the near end.

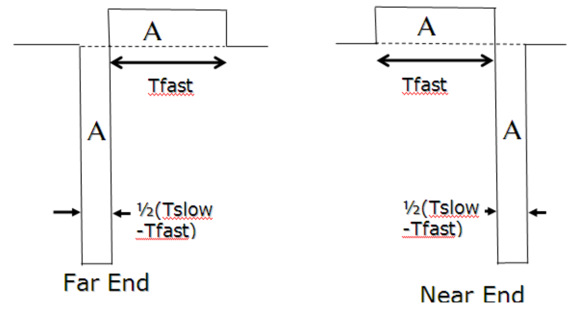

Fig. 13. Step response of far end and near end Zfe loads on dielectric line for Case 3 as in Fig. 12. These are the L-pulses L_{fe} and L_{ne}.

V. Induced Currents From Perpendicular Cable Shield Pulse

Now we use the eigenpulse solution to deduce the general form of the induced current response to the perpendicular cable shield pulse, Case 1 configuration. The cable is plugged into the platform and the far end, charged, is connected to ground, threatening the platform. Assuming ideal matched conditions for an eigenpulse solution, the current step propagating along the shield heading away from the ground plane will have nonuniform amplitude, following Fig. 2. For a platform at some distance, sitting in a low field, that current pulse on the shield could be very weak by the time it reaches the platform. But this does not mean that the platform data lines escape, as the main effect relates to the induced current on the data lines near where the pulse occurs at the far end. This is where the charge is bunched up, the current is huge and therefore the induced current is substantial. As the inner line has constant impedance, the initial induced currents at that end propagate to the platform just as they do for the uniform outer line impedance case, with the same kind of time compression as for the W-pulse (Fig. 14, where we use the same methods as above to deduce the general character of the inductively-coupled signal). This rather vigorous initial pulse is followed by a long tapered pulse of equal area and opposite polarity, as shown. The overall polarity depends on the sign of the inductance, which could be negative due to braid inductance as discussed above; the pulse of Fig. 14 would result from positive charge on the shield, as in Fig. 2, in the case of net negative inductance. This is what happened with the lab data of Fig. 4.

The perpendicular cable shield pulse case does of course involve retarded potentials, and thus is ultimately a rather complicated field problem, not strictly a coupled transmission line problem. This means that using the impulse response (Fig. 8) and the convolution integral (Eq. 1) is an approximation. That approximation should apply over the portion of the cable where there is substantial current flow, i.e., where the field is fairly strong. The size of that region thus determines the time scale of Fig. 14. But the wave generated in the inner transmission line due to the high-field region on the outer shield will certainly propagate the length of the cable and reach its target, and will resemble what can be calculated from Eq. 1.

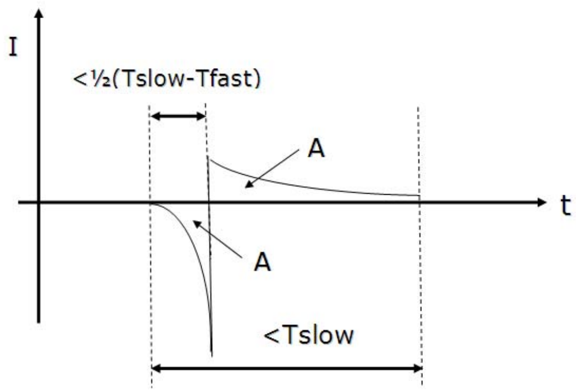

Fig. 14. Sketch of induced current response on data lines, resulting from a pulse as in Fig. 2 on the shield. With inductive coupling only, velocity contrast causes a large short negative pulse followed by a long positive pulse, thus a latchup hazard. The strong initial signal at the far end (shield touching ground, Fig. 2) induces current that flows smoothly on the dielectric line, giving the time-compressed short initial spike at the near end load, despite the weak E-field in that vicinity.

Clearly the strong initial time-compressed pulse of Fig. 14 (followed by a pulse of the opposite polarity) presents a latchup hazard, and has the potential for damaging silicon components. We have long believed that some kind of bipolar, pulsed, or transient latchup test would prove to be a worthy complement to our DC latchup test. While our DPZ test does inject a sharp current spike, it is unknown whether DPZ is the ideal pulsed latchup test for external ports, or if a true bipolar test is needed, but DPZ a good start. The strength of the inductive coupling to the data lines is believed to be fairly weak (see [1] and references therein), 1-3% at most, so there should be limits on how strong a DPZ test is meaningful. Even at 3% coupling, a 25 kV shield pulse would scale down to 750V, although the shield pulse would be transformed into a compressed bipolar pulse as described for the various cases above. Nonetheless, it appears that 1kV DPZ tests the external ports with generous margin, and leaves no danger of latchup due to shield pulses.

The other way to test for platform latchup hazards due to cable discharge is to apply the standard IEC 61000-4-2 test aggressively to cable connections. A worst-case cable would be "leaky", perhaps having extra inductive holes to couple signal more strongly than the 1-3% cited above. As seen in Fig. 9 and related discussions, the induced currents will automatically be sharp and bipolar, as they should be. The shield will protect the internal platform and chip components, but only up to a point. Remembering to apply IEC tests of this sort, to a platform with cables connected, may be the key element of success.

VI. Conclusions

Cable discharge events (CDE) begin with a primary pulse to the shield or wire, found to have log-tapered form for a charged cable at right angles to a ground plane. For shielded cables, the induced signal line pulses can be analyzed through step response and impulse response. The step response, called the W-pulse, and related "eigenpulses" for various cable configurations, give the basic functions from which induced current effects can be calculated.

The main features of the induced current pulses are that they are bipolar, and have sharp transitions. They are bipolar because the coupling from shielded cables to internal lines is almost all inductive, and they have sharp transitions because of the velocity contrast between the speed of waves on the outer cable (air) and the inner cable (dielectric). This is why there is still a system latchup hazard due to CDE on shielded cables, despite the protection and vastly reduced pulse magnitude afforded by the shield. Having connected cables as part of the regular IEC platform test should help test for cable discharge latchup hazards.

Acknowledgments

The author thanks Steven Poon for coupled-line CAD simulations, thanks Tina Cantarero, Arlene Wakita and Bruce Chou for lab data, and also thanks Ted Spanos for manuscript review.

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