Conductivity and Time-Constant Measurements on Magnetically-Agitated Electrophotographic Developer Using the Method of the Compensated Probe

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Abstract

The general concept of developer "conductivity" is known to play a role in development rate and efficiency, but a packed powder cell measures conductivity under conditions quite different from an actual toning nip. For a two-component developer with magnetized carrier, the developer is magnetically agitated as it flows through the toning zone, while in the packed cell it is static. A test cell was constructed which agitates a thin layer of developer and subjects it to brief voltage pulses, as it would realistically experience in a nip transition. In many cases of interest the developer is insulating enough that most of the current is capacitive, making actual toning current difficult to discern. This particular problem can be overcome by designing the measurement circuit as a compensated probe, that is, with a capacitor in parallel with the current sense resistor. Example waveforms give evidence of a nonlinear conduction process in toning.

Introduction

The small particle developer or SPD toning process, invented by Miskinis and Jadwin at Eastman Kodak in 1983, is at the heart of the electrophotographic process in the Digimaster 9110 and the Nexpress 2100, the flagship digital black-and-white and color presses offered by Heidelberger Druckmaschinen.[1] While this commercial success attests to the basic soundness of the technology, the ever-increasing customer demands for high and stable print quality at lower cost present an ongoing challenge to its engineers.

SPD differs from conventional two-component magnetic brush development in that the carrier component consists of relatively small permanently magnetized particles rather than magnetically soft ones, and the developer flow is accomplished in large part by the action of a counterrotating magnet core inside the toner roller. As described earlier by Miskinis and Maher, the interaction of the magnetic field of the core with the carrier magnetic moments causes the carrier particles to form magnetic chains, which tumble and flow over the surface of the roller, in the opposite direction to the magnet rotation.[2,3] (The developer flow is cocurrent with the motion of the photoconductor.) This greater agitation of the SPD developer in the toning zone is credited with more efficient and artifact-free development than conventional.

Relatively little analytical work has been done on SPD and our understanding of some important details is limited. Lacking quantitative theory with predictive power, the only way to get really dependable results is by extensive experiments on a prototype which is close to full process, and therefore also expensive, complex, and tedious to work with.

The essential action of toning takes place of course in the toning nip where the developer meets the latent image. In addition to the toning roller, the production toning station requires other elements to replenish the toner, mix it into the developer, feed the toning roller and strip depleted developer from it. The engineering of these flow- and mixing-related parts is vital and absorbs considerable resources. Nonetheless it seems reasonable to hope that useful information could be obtained from a simplified offline test fixture which focuses on the fundamental action in the toning zone and omits the full process flow handling. Such was the approach taken by Gutman and Hartmann for their study of conventional development, and it should be fruitful for studying SPD as well.[4]

The most basic view of toning that captures any dynamics is that of an RC circuit. A current of toner particles passing through the developer nap charges the capacitance of the photoconductor. Because it takes a voltage difference across the nap to force the current, the concept of electrical resistivity can be, roughly speaking, applied to the developer. The intent of the work described here was to develop an offline measurement of the toning conductivity of SPD developer under conditions realistically representing the toning zone, particularly the magnetic agitation. In terms of the conductivity of the carrier itself, SPD is insulative.

An excellent starting point for an offline SPD fixture is the device described by Maher, in which a subgram sample of developer is placed on a flat horizontal nonmagnetic disk electrode, and is agitated by a multipole ring magnet rotating beneath in the horizontal plane.[3] As on the toning roller, the developer flows opposite to the magnet rotation, in this case in a ring-shaped path above the magnets. Toner is developed onto an upper disk electrode 1 cm above, upon the application of DC voltage to the lower plate. This device has been routinely used for assessing the health of developer, by measuring its toner concentration and charge-to-mass (q/m) ratio. To do so the device is typically run for 30-120 seconds at 2-3 kV in order to remove all the toner from the sample. Maher investigated the rate of toner extraction and found it to be an exponential function of runtime, initially high and then tapering off. He further studied the dependence of the time constant on agitation rate (magnet rpm), applied electric field, as well as carrier and toner tribocharging additives, reporting results in the range of 13-81 seconds.

The conditions the developer experiences in this device are actually not very much like those in the toning zone. In the toning nip the toned surface is in contact with the developer, less than 0.5 mm from the shell, not 10 mm away across an air gap. In transiting the nip the developer experiences a pulse of electric field about 15-30 milliseconds long, not 30 seconds. Only part of the available toner is extracted, not all of it. Finally, the applied electric field strength might be up around 10 kV/cm, not just 2-3.

The work described in this paper uses the same basic device as Maher, but modified and operated such that the developer experiences more realistic conditions, as in the toning zone. The pole flip rate of the magnet ring was 200 Hz. The plate spacing was reduced to 0.38 mm and the DC bias replaced with a balanced square wave of 500v amplitude (1kV peak to peak) at about 20 Hz, slow enough that each half-cycle is about as long as a nip transition or more.

The obvious way to measure the resulting current between the plates would be to insert a current sense resistor in series, forming a resistive potential divider. However the resistivity of the developer could be expected to be fairly high and capacitive loading is a generic problem with pulse and AC current measurements at high impedance. Because of the parasitic capacitance of the plates in parallel with the developer sample, the division ratio becomes frequency dependent and at high enough frequency, most of the current measured is capacitive and has nothing to do with the toning current. A solution to this is the compensated potential divider.[5]

Experimental

Figure 1 is a sketch of the measurement circuit. A square wave is applied to the upper plate by a Trek 10/10 amplifier. A simple low-pass filter with a 14 kHz cutoff suppresses any high-frequency ripple from the amplifier. To such an AC or pulsed voltage, the developer between the plates appears as a resistance R1 in parallel with the capacitance C1 of the plates and their wiring, which was determined to be about 100 pf. The current is sensed using another parallel combination R2C2. The idea is that it should have the same time constant, but much lower impedance than the developer, that is, the RC product is the same but the C is higher and the R is lower. When R2 is adjusted to make the time constants match, the voltage division ratio should be the same at all frequencies, so an applied square wave will be faithfully reproduced across R2C2. If R2 is too high the wave shows "undershoot", too low and it shows "overshoot." (See Figures 6-8 for simulation.) Thus, doing the measurement consists of tuning R2 until the input and sensed waveforms match. At that point the ratio of their amplitudes is the division ratio. One then measures R2 and multiplies by the division ratio to get R1, the developer resistance. The capacitor C2 at 0.01 uf was chosen aiming for a 100x division ratio; it actually turned out to be about 80x. Gigohm AC high voltage probes were used to measure the input and output waveforms for oscilloscope display.

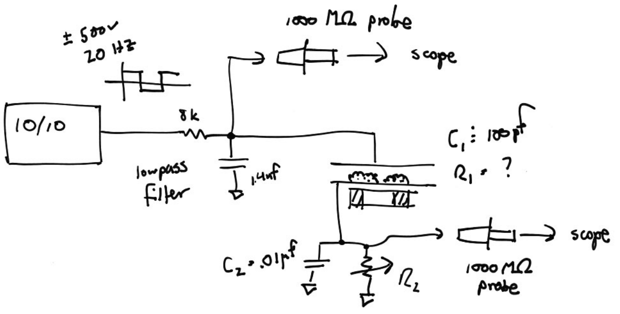

Figure 1. Measurement circuit

Initial Observations

There was no difference between a stationary, unagitated developer and empty plates, that is, the resistance of static developer was too high to measure. Agitated developer however was more conductive and did have a measurable resistance.

The upper limit of R1 we could measure was set by the parasitic leakage resistance of the current-sense capacitor C2, that is, its self-discharge. This was roughly 20 Mohm thus the maximum sample resistance we could measure was about 1.6 Gohm.

When the circuit is tuned the voltage across C1 and C2 is steady except when the square wave switches polarity. Thus the current drawn from the amplifier was very low except at the switching transitions, when it spiked to the 10 ma limit of the amplifier. Another way to think about how the circuit works therefore, is that during the switching all the current goes through the capacitances, so they influence the voltage division just after switching (at the "beginning" of each pulse.) The system then begins evolving toward an equilibrium where all the current goes through the resistances and they determine the division ratio. The overshoot and undershoot can be regarded as a result of mismatch between the capacitive and resistive division ratios.

Toner Concentration

Table 1 shows the results of an experiment with two sample sizes and two toner concentrations – carrier only and 6% toner by weight. Three samples of each combination were tested. Each was agitated for two minutes before voltage was applied. Figure 2 plots the developer sample resistance R1 calculated from the tuned value of R2 and the measured division ratio. Notice that the pure carrier is much less conductive by a factor of 5 to 7, which implies that there is toning current in the 6% toner samples.

Table 1. Toner Concentration and Sample Size Experiment

Toner conc wt %	Load (g)	Area cm^2	**Sense R2 Mohm**	Vapplied	**Vsensed**	Sample R1 Mohm	R2 C2 TimeConst ms	Sample r1 ohm-cm	Sample S/cm2	Est. PC toning time ms
0	0.3	12.65	8.040	1070	15	574	84	1.9e11	1.4e-10	726
0	0.3	12.65	8.650	1070	14.5	638	91	2.1e11	1.2e-10	807
0	0.3	12.65	8.450	1070	15	603	89	2e+11	1.3e-10	762
0	0.4	15.25	6.240	1070	14	477	66	1.9e11	1.4e-10	727
0	0.4	15.25	4.710	1070	15	336	49	1.3e11	2e-10	512
0	0.4	15.25	6.170	1070	14	472	65	1.9e11	1.4e-10	719
6	0.3	12.65	1.700	1070	15	121	18	4e+10	6.5e-10	153
6	0.3	12.65	1.524	1070	16	102	16	3.4e10	7.8e-10	129
6	0.3	12.65	1.728	1070	14	132	18	4.4e10	6e-10	167
6	0.4	15.25	1.300	1070	16	87	14	3.5e10	7.5e-10	133
6	0.4	15.25	1.012	1070	19	57	11	2.3e10	1.15e-9	87
6	0.4	15.25	1.030	1070	17.5	63	11	2.5e10	1.04e-9	96

The larger samples occupy more area on the plate and would thus show lower resistance even if the resistivity were the same. Calculating the volume resistivity or the conductance per unit area takes the area into account and the difference between the sample sizes is reduced, as shown in Figure 3 and 4.

The time constant listed in Table 1 is R2C2, which is the same as R1C1. It could be interpreted as the dielectric relaxation time of the agitated developer itself, except that C1 includes a lot of extra capacitance of the plates and wiring outside of the area covered by developer. It is probably fair to say it is a loose upper bound on the dielectric relaxation time.

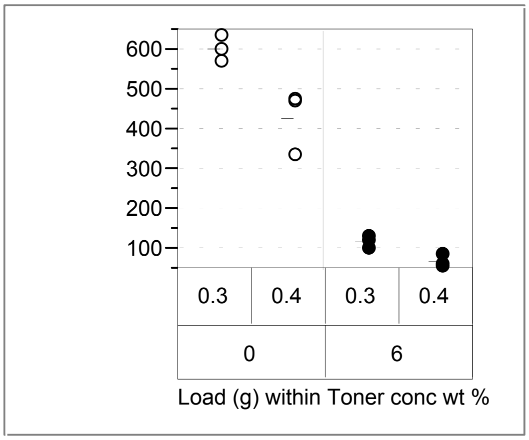

Figure 2. Developer resistance R1 (Mohm).

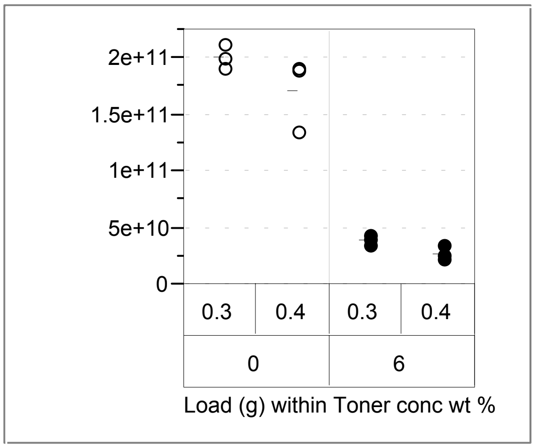

Figure 3. Developer resistivity (ohm-cm).

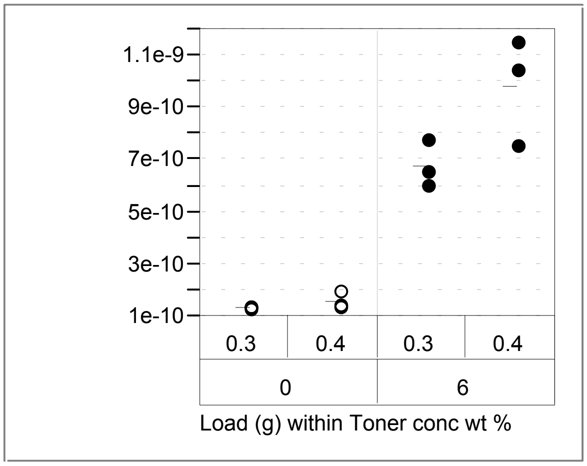

Figure 4. Developer conductance per unit area (S/cm^2).

To get an idea of what these results might imply as to an actual development time constant, the last column in Table 1 shows a time constant calculated from the developer conductance per unit area and a hypothetical photoconductor capacitance per unit area. (100 pf/cm^2/

Sample S/cm^2), in ms. For the 6% toner cases it was about 100 ms. That is much shorter than what Maher reported, but from experience with the real toning station it still seems too long, by a factor of two or three. The discrepancy may be due in part to the fact that the actual toning station uses a higher-frequency component of toning bias, about 1 kHz, to enhance the development rate. It may be more realistic to use pulses of one polarity or with blanking intervals, instead of a balanced square wave, which is presumably scavenging one plate while toning the other.

Evidence of Nonlinear Conduction

Another part of the discrepancy may be related to an observation of waveform distortion which could not be nulled out by adjusting R2. This distortion was present only with the 6% toner samples, not the pure carrier. It was not caused by the low-pass filter. It suggests to me that the sample resistance was changing over the course of each voltage pulse. To explain, the next series of plots compares a simulation of the measurement circuit to the actual 'scope traces. In this test the frequency was 13 Hz and the sample size 0.4g. The simulated circuit is diagrammed in Figure 5; it includes probe loading and finite output resistance of the amplifier.

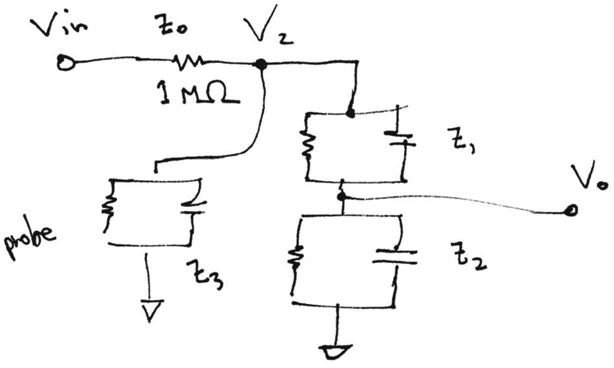

Figure 5. Linear circuit for simulation.

Figures 6, 7, and 8 show what the simulation predicts when the time constant of the sensing network R2C2 is too slow, just right, and too fast (R2=3.5, 0.91, 0.70 Mohm.)

Here v2 is the voltage applied to the plates and vout is across R2C2. The other parameters are constant as follows: R0=1 Mohm, R1=80 Mohm, C1=120 pf, C2=10.5 nf, R3=1000 Mohm, C3=50 pf.

Compare the measured traces in Figure 9 (R2=3.2 Mohm) with Figure 6. At the beginning of the pulses, it looks like the sensing time constant is too slow, as in simulation, but after 25 ms or so the trace flattens out and it looks about right.

In trying to tune the circuit, there wasn't a value of R2 which made the trace flat. Figure 10 shows the trace for R2=1.5 Mohm, which was about the best compromise. This shows "bowing" distortion – at the beginning of the pulses the slope is positive and the time constant looks too slow. At the end the slope is negative and it looks too fast. When R2 was adjusted to match the beginning of the pulse it came out to be 1.0 Mohm.

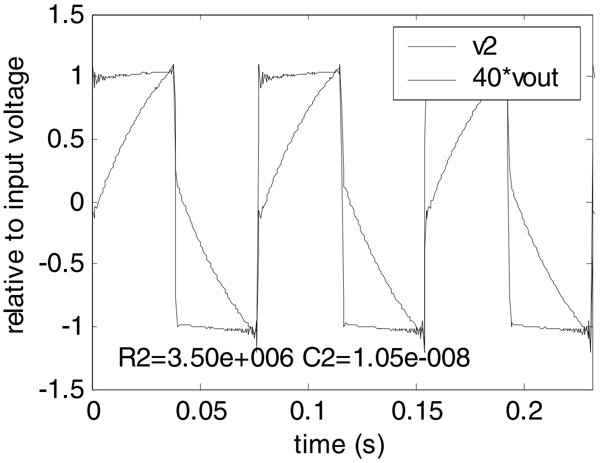

Figure 6. Sensing time constant too long.

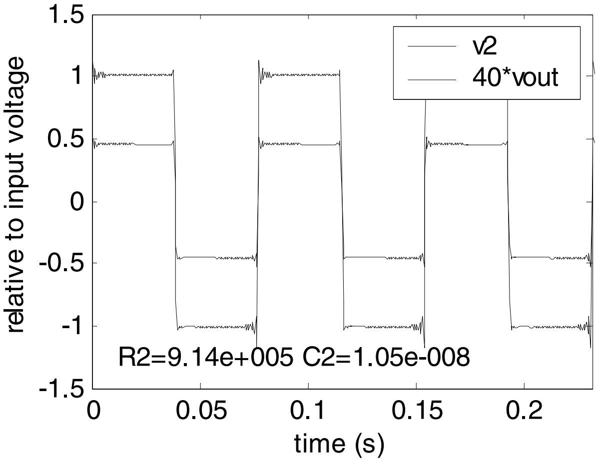

Figure 7. Sensing time constant just right.

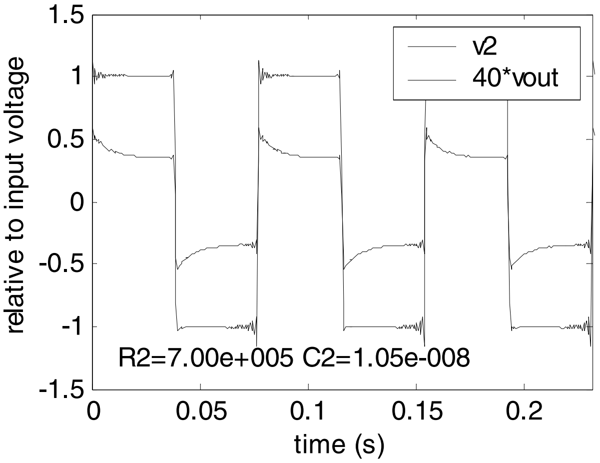

Figure 8. Sensing time constant too short.

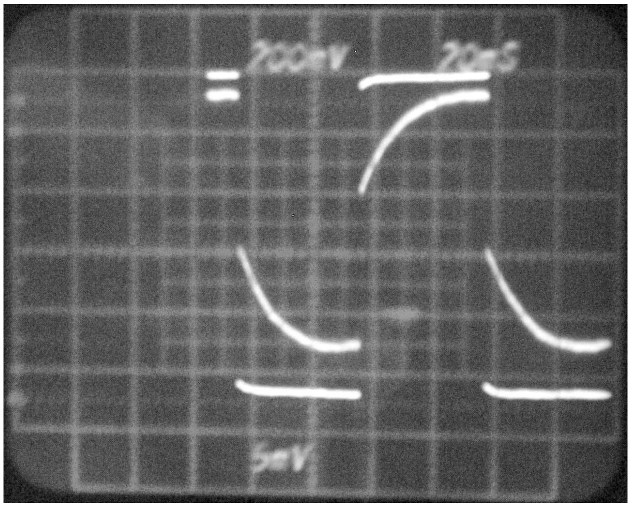

Figure 9. Compare to Fig. 6 – measured trace flattens out midway through the pulse.

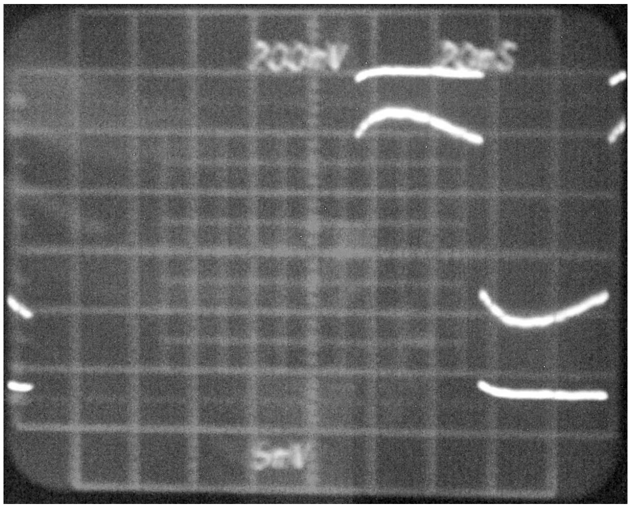

Figure 10. Compare to Fig. 7 – Sensing time constant appears too high at the start of the pulse, too low at the end.

Because an R2 of 1.0 Mohm matches the beginning of the pulse while an R2 of 3.2 Mohm matches the end, the developer is behaving as if its time "constant" is faster at the beginning of the pulse than at the end, by a factor of three (10 ms versus 30 ms.) In the experiment of Table 1, R2 was being adjusted to the "compromise" value – it would have been lower if adjusted to match the start of the pulse, which would bring the calculated development rate closer to what the full process seems to achieve.

The implication for developing onto the photoconductor is that the toner conduction process is nonlinear in an unfortunate way – the effective resistance of the developer to the toning current increases over the course of the nip transit. Thus the toning rate would fall off faster than exponential over that time.

It is perhaps not surprising to find some nonlinearity. Ohmic conduction typically requires that the number density and charge of the particles is independent of the applied field, and that their velocity is proportional to the applied field (constant mobility.) [6] It is not clear that any of this is necessarily the case for an SPD nap. Consider the basic toner supply. To form a maximum density solid image requires about 35 mg of toner per cross-track inch per second at 30 cm/s. A developer flow rate of 2-3 g/in/sec at 6% toner contains 120-180 mg/in/sec. Thus the image may demand 20-30% of the available toner, which is not a trivial fraction. One could begin to imagine what space charge or toner starvation effects might come into play; there is still quite some opportunity for fundamental work of this kind on SPD.

Conclusion

The test fixture and compensated-divider technique described did work – we were able to measure the effective conductivity of small samples of SPD developer under magnetic agitation and with pulsed electric field, emulating an actual toning nip transit. The different response of stationary, agitated, and toner-free developer indicate that most of the conduction was due to toner current. The conductivities obtained did seem too low by about a factor of two or three, considering how well an actual toning station performs. However, the distortion of the measured current waveform can be interpreted as evidence that the effective developer conductivity was varying during each pulse, falling by about a factor of three from start to finish. The technique used here gave a mid-pulse compromise value. It is also possible that the measured conductivity could be raised by making the electric field pulses even more realistic, i.e., by including blanking intervals or a high-frequency AC component.

I hope that the test method described will prove to have predictive value and can be used in the future for preliminary testing of design and materials changes, and for fundamental study of the toner conduction process in SPD.

Acknowledgements

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Biography

Graham S. Wright received his Ph.D. in Electrical Engineering from the University of Illinois in 1993. After working with the University's SunRayce'95 solar car team, he joined Kodak's Office Imaging division in research and technology development, and moved to Nexpress in 1999. He currently lives in Brockport, NY, USA, and is a member of IS&T and IEEE.